PROCEEDINGS

Potential Applications
of
Fluidized Bed Combustion in Canadian Industry
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SOMMAIRE DES DELIBERATIONS

Applications possibles
de
la combustion en lit fluidisé dans l'industrie canadienne
Un atelier commandité
par
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INTRODUCTION

The following papers were prepared by the authors for a "state of the art" seminar in Calgary, Canada, on May 27, 1982. The seminar was presented by the Canadian Institute of Energy, and co-sponsored by the Canada Centre for Mineral and Energy Technology (CANMET), Energy, Mines and Resources Canada.

The purpose of the seminar was to present an overview of current technology in Atmospheric Fluidized Bed Combustion in Canada, Japan and the United States, and to outline and encourage potential applications of this technology in Canadian industry.

The Canadian Institute of Energy wishes to take this opportunity to thank all of the participants at the seminar and, in particular, to thank the CANMET personnel who made such a successful event possible.

INTRODUCTION

Les articles qui suivent ont été écrits par les auteurs dans le câdre d'un séminaire pour faire le point sur l'état d'une question à Calgary, Canada, le 27 mai, 1982. Le séminaire fut animé par l'Institut Canadien de l'Energie et co-commandité par le Centre Canadien de la Technologie des Minéraux et de l'Energie (CANMET), Energie, Mines et Ressources Canada.

L'objectif du séminaire était de présenter un apperçu de la technologie de l'heure dans le domaine de la combustion en lit fluidisé au Canada, au Japon et aux Etats Unies de même que de mettre en évidence et d'encourager ses mises en application possibles dans l'industrie canadienne.

L'Institut Canadien de l'Energie désire remmercier tous les participants et en particulier le personnel de CANMET qui a rendu possible l'organisation de cet évènement couronné de succès.

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A REVIEW OF MAJOR CANADIAN ACTIVITIES IN FLUIDIZED BED COMBUSTION

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INTRODUCTION

Canadian interest in fluidized bed technology stems from reasons similar to those which apply in many other countries. These are: a need to rely increasingly on coal as a major source of energy for heating plants, industrial steam raising, and thermal generation of electricity: short-comings of existing combustion technology for coal in terms of economic and environmental considerations; and the potential of FBC technology to achieve a significant level of commercial deployment in the next ten to twenty years. However, while the range of possible applications for FBC in Canada is broad, the potential market in each area of application is rather limited, a fact which tends to hinder implementation of the technology through commercial forces alone. The government of Canada has therefore deemed it in the national interest to support the development of FCB technology, as indeed it supports the development of other new energy technologies, in the expectation that this will expedite its contibution to Canada's energy alternatives.

The present paper, while by no means comprehensive, identifies the main areas for the potential application of FBC technology, and summarizes the major research development and demonstration projects that are now in place.

POTENTIAL APPLICATIONS OF FBC IN CANADA

Utilization of High-Sulphur Coals

The capability of fluidized-bed combustion to burn high-sulphur coals in an environmentally-acceptable manner while avoiding the disadvantages of flue gas scrubbing is undoubtedly the major force driving the development of FBC technology in North America. This is true of Canada as well, although not to the same extent as in the USA. Canada does have an acid rain problem, but at least until the turn of the century, the impact of FBC is likely to be limited to our Atlantic provinces, where indigenous deposits of bituminous coal, ranging from 3% to 9% sulphur, are available to replace imported oil.

In central Canada, (Quebec and Ontario) the electric utilities foresee no immediate expansion of coal-based thermal power generation; instead they are developing hydraulic and nuclear power to meet additional needs. Industry makes some use of coal, but has imported low-sulphur coal and natural gas among its fuel options. Western Canada enjoys ample reserves of low-sulphur coals for both utility and industrial purposes, supplemented by natural gas and hydraulic power.

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Thus, with some exceptions, the short-term need for FBC technology to control SO_2 emissions in Canada is limited to the Atlantic provinces. There, however, a full spectrum of boiler sizes to meet heating plant, industrial and utility applications is required.

Combined Firing of Coal and Wood Waste

Pulp and paper is one of Canada's major industries and therefore a correspondingly large energy user. It makes substantial use of wood waste, co-fired with fossil fuels, for generation of process steam and electricity, but existing technology presents some constraints on both combustion performance and fuel flexibility. It is felt that carefully-designed FBC boilers burning wood waste supplemented with coal could offer a significant step towards energy self-sufficiency.

Utilization of Coal Washery Rejects

The Canadian coal industry produces several million tons of coal washery rejects per annum as a result of coal upgrading operations, primarily in western Canada. These rejects have an energy equivalent of several hundred megawatts, but theirhigh ash and moisture content preclude utilization by conventional combustion systems. However, FBC technology offers the potential for employing this low-grade energy resource to supply hot gas for coal drying, or, on a large scale, to generate electricity.

Utilization of Unreactive Fuels

A small but strategically important role for FBC technology lies in the utilization of fuels which, albeit high in calorific value, are relatively unreactive, and therefore are difficult to burn in conventional combustion systems. One example is byproduct coke from oil sands extraction plants. This material is typically high in sulphur (5 to 8%), low in volatile matter (0 to 12%) and difficult to grind; a combination of properties to which FBC is well-suited. Other examples of unreactive fuels are deposits of partially-oxidized bituminous coal which occur in western Canada. These, being depleted in reactive macerals, present problems of ignition stability and carbon carry-over when burned in conventional pulverized-coal-fired furnaces.

Thermal Power Cycles Having Improved Efficiency

Canada,being dependent upon coal for about 20% of its electicity, has ample reason to foster the development of advanced coal-to-electricity cycles. The candidate technology with the greatest potential for improved efficiency appears to be a combined cycle involving a pressurized fluidized bed combustor, a gas turbine, and a conventional steam turbine. This is recognized as a long-term possibility at best, with an enormous requirement for research, development and demonstration.

GOVERNMENT-SUPPORTED ACTIVITIES IN FBC

In Canada, fluidized-bed combustors have been in commercial use for a number of years, but as incinerators for waste materials such as wood waste, sewage sludge and sulphite liquor. Energy recovery is practised in some installations by means of waste heat boilers. Until the present decade, there were no Canadian suppliers in a position to offer FBC boilers burning coal. Recognizing the potential contribution that FBC technology could make toward the goal of Canadian self-reliance in energy, the federal government undertook to accelerate implementation of this technology by supporting a comprehensive program of research, development and demonstration. Planning and implementation of the program have been mainly in the hands of the federal departement of Energy, Mines and Resources (EMR), primarily through its technological branch, the Canada Centre for Mineral and Energy Technology (CANMET). Work is carried out by a combination of in-house R & D, contracted-out R & D, demonstrations co-funded with other agencies, and conceptual designs and economic analyses co-sponsored with industrial partners. The present paper describes four main components of the program in which work is presently well under way.

These are:

a) The CFB Summerside Demonstration Program

b) Studies Related to Industrial Combustors and Boilers

c) The NSPC 10,000 h. Corrosion Test Program

d) Supporting Pilot-Scale Research and Development

THE CFB SUMMERSIDE DEMONSTRATION PROJECT

Scope and Objectives

The "CFB Summerside Project" is in the final stages of erecting a two-boiler heating plant, as the first demonstration of coal-fired FBC boilers in Canada. The boilers have a maximum capacity rating of 18,000 kg/h of steam each, burning coal containing about 5% sulphur as the primary fuel, with co-firing of wood chips on a demonstration basis, and will capture sulphur by means of limestone. The plant is located at Canadian Forces Base Summerside in the province of Prince Edward Island; the project is co-sponsored by Energy, Mines and Resources Canada (EMR) and the Department of National Defence (DND).

EMR objectives are:

a) to demonstrate AFBC as a viable, clean, "off-oil" technology, and;

b) to develop Canadian manufacturing capabilities and operating expertise in AFBC technology.

DND objectives are:

a) to replace an obsolescent coal-fired steam plant at minimum life-cycle cost but with environmentally-acceptable technology capable of utilizing the only secure fuel supply in the area, which is high-sulphur coal,

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b) to eliminate a local pollution problem caused by the plant to be replaced, and;

c) to reduce the number of heating plants on the base from two to one, and so reduce staffing requirements.

Project History

The Gulf of St. Lawrence, where CFB Summerside is located, faces a severe climate. Daily mean temperatures are sub-zero celsius for five months of the year and average wind speeds are approximately 25 km/h. Steam demand on the base varies from a summer month average of 2200 kg/h to a winter peak of 25,000 kg/h. Steam conditions for the base heating system are 965 kPa (140 psig) saturated.

With the exception of limited quantities of wood grown on Prince Edward Island all fuel has to be shipped across water. Fuel oil in the Atlantic region must be imported and hence has the dual disadvantage of high cost and insecure supply. High-volatile bituminous coal is available at reasonable cost from the two neighbouring provinces of New Brunswick and Nova Scotia but quality is poor in several respects, particularly for stoker grate applications. The coal is strongly caking, sulphur ranges from 3 to 8%, ash content is approximately 20% and ash softening temperature is low Chipped woods, obtained from land clearing in connection with reforestation projects on Prince Edward Island, constitutes another possible source of fuel, although neither the cost nor the extent of supply have been clearly established. However, Canadian industrial experience with FBC incineration of wood waste has indicated that co-firing of coal and wood waste is feasible. This, together with the capability of FBC to utilize coal having the characteristics just described, led EMR and DND to an agreement early in 1977 to co-sponsor a demonstration heating plant using, if feasible, both fuels.

A design requirement was developed of which the following are the major points:

1. The two-boiler heating plant is to be added to the existing No. 2 plant at the base. The existing boiler in No. 2 plant are to continue in service, but after successful commissioning of the FBC boiler the existing No. 1 plant shall be taken out of service.
2. The new plant addition shall house, as well as the FBC boilers, all necessary systems such as materials handling, steam, condensate, feed-water and electrical supply, with necessary cross-connections to integrate the new boilers in No. 2 plant into one steam supply system.
3. The coal delivery and bunkering system shall be able to cope with wet or frozen coal.

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4. The coal handling system shall be so arranged that there will be no interruption of coal supply to the boilers should any one conveyor have to be taken out of service for repair or maintenance while the plant is operating.

5. A comprehensive system for reception, storage, preparation and handling of coal, limestone, wood chips, fly ash and bed residue shall be included to meet the following specifications:

   Coal Storage: 96 hours supply for a steaming rate of 25,000 kg/h (55,000 lb/h)

   Limestone Storage: 96 hours supply for a steaming rate of 25,000 kg/h (55,000 lb/h)

   Woodchips Storage: 12 hours supply for 30% of heat input for steaming-rate of 25,000 kg/h (44,000 lb/h)

   Bed Drain and Fly Ash Storage: adequate to hold the products from 96 hours of operation at a steaming rate of 25,000 kg/h (55,000 lb/h).

   The criterion of 96 hours storage capacity was selected to ensure that transportation of the materials external to the plant could be avoided over long week-ends.

6. An auxiliary power unit (diesel generator) large enough to supply emergency power to operate one AFBC boiler only in case of power failure, shall be provided.

7. The FBC boilers shall use an overbed feed system, and coal supplied to the plant will be sized at 50 mm x 0 (2 in. x 0).

Further design requirements, including the allowable stack emissions, are given in Table 1. Particulars of the design coal, the fuel with which guarantees of boiler capacity, efficiency and emissions are to be met, are given in Table 2. The supplementary fuel, wood chips, is described in Table 3. It is also intended to carry out demonstration tests with fuel of lower quality than the design coal, and the analysis of this "demonstration fuel" is given in Table 4. The design contract required that the FBC boilers burn the demonstration fuel successfully, but no performance guarantees apply. Table 5 provides analytical data for the limestone selected as the sulphur sorbent.

In 1977, FBC boilers were not available from Canadian suppliers. To transfer the requisite technology to Canadian industry, EMR sponsored a series of competitive design contracts, the details of which are recorded elsewhere (1). For present purposes it suffices to say that on January 5th 1981 detailed designs and firm price proposals for construction of the desired heating plant were received from two bidders. One was Foster Wheeler Ltd., which offered a boiler design based largely upon the technology

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of its American parent; the other was Dominion Bridge-Sulzer Inc., which under licence from Babcock and Wilcox Ltd. of the U.K., offered a boiler of essentially British design. The EMR/DND bid evaluation team, after careful review of the two proposals, concluded that both fully met the technical requirements. Since the Foster Wheeler proposal offered a substantially lower price, that firm was awarded a contract on February 26th, 1981, in the amount of $13,135,635 Canadian, for construction of the complete plant addition with two FBC boilers.

The following sections describe the main features of the Foster Wheeler design which is now ready for commissioning. The previously referenced report gives additional details as well as a description of the Dominion Bridge-Sulzer design (1).

Plant Layout

The layout of the new plant and its relationship to the existing plant are shown in Figure 1. The control room has been placed to permit centralizing the operation of both the new and the existing boilers. A basement was required in order to keep the height of the building under the aircraft flight interference plane associated with a nearby runway. Since the boilers are shop-assembled packages, the building structure was designed to permit skidding the boilers into the building on their backs, then hoisting them into position. This permitted erection of the building and fabrication of the boilers to proceed simultaneously.

For each boiler, the gas path is as follows. The forced-draft fan, situated below grade, draws boilerhouse air through an inlet silencer and delivers it to the fluidized bed plenums at the base of the boiler. The flue gases leaving the boiler pass into a mechanical dust collector, then an economizer, then a baghouse, and finally into an induced draft fan which discharges to atmosphere via a free-standing stack which passes through the building roof.

At-plant storage bunkers for coal and limestone are located within the building to minimuze the handling difficulties under freezing conditions.

Materials Storage and Handling Systems

A. Coal

Coal is normally delivered to the base during the summer months and stockpiled out-of-doors. During the fall and winter it is exposed to rain snow and freezing conditions, a fact which was taken into account insofar as possible in the design of the plant bunkering system. Figure 2 shows a simplified flow diagram, together with storage and handling capacities.

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Delivery from the stockpile to the plant is made by dump trucks which discharge through a "grizzly" with 75 mm square openings into a hopper from which the coal is fed, by means of an elevator, to a vibrating screen. Here oversized coal is separated and passed to a crusher for sizing. The screenings and the crushed coal rejoin and are elevated to a transverse conveyor passing over the tops of four coal bunkers, each having a capacity of 75 tonnes. These are arranged so that for normal operation two of them will serve one AFBC boiler while the other two will serve the second AFBC boiler. The discharge cones are lined with stainless steel and fitted with vibrating bin discharges to reduce the possibility of "rat-holing".

From the bin dischargers, the coal from each pair of bunkers is elevated to a ready-use bin for the associated boiler. Alternatively, by means of a transfer conveyor, shown in Figure 2, either ready-use bin can be replenished from either pair of bunkers. This ensures that if any one item of transfer equipment between the bunkers and the bins fails, both boilers can still be operated.

Coal is extracted from the bins at controlled rates by belt-type weigh feeders, one per boiler, and transferred by a split chute to the two stokers per boiler.

B. Limestone

The method of handling limestone is similar to that for coal, except that it is not intended to provide a major stockpile of limestone at the base. With limestone transported a relatively short distance from New Brunswick, little difficulty is foreseen in delivering directly to the plant as required. A small stockpile will be provided to guard against possible interruption of deliveries due to ferry difficulties or seasonal load limitations on roads.

It is intended to buy linestone sized as required for the fluidized beds. However, the possibility of having to deal with frozen lumps has been recognized, and therefore after being dumped through a "grizzly" the limestone passes through a screen and crusher arrangement similar to that for coal. It is then transferred by elevator and belt conveyor to two storage bunkers, one per boiler. Each has a capacity of 68 tonnes.

From the bunkers the limestone is elevated to ready-use bins, one per boiler, from which it is taken at controlled rates by two weigh feeders per boiler, and fed through drop pipes into the respective fluidized beds.

As the provision of limestone is not critical for the production of steam no provision has been made to supply limestone from either bunker to the ready-use bin of the opposite boiler.

The flow diagram for this system is also shown in Figure 2.

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C. Wood Chips

It had originally been intended that a complete storage and handling system be provided so that wood chips could be used as a supplementary fuel on a continuous basis. Consideration of the overall cost of such an installation, together with uncertainties of price and long-term continuous sypply of wood chips for this particular plant, led to a modified approach in which the use of wood chips could be demonstrated but not on a continous basis. This was done by retaining within the design the two ready-use wood-chip bins above the boilers but deleting the originally-intended bulk storage and handling facilities.

Instead, it is proposed to use the coal bunkering facilities for receiving the wood chips and elevating them to the transverse conveyor across the top of the coal bunkers. By means of an additional gate on the transverse conveyor, shown in Figure 2, the wood chips can be fed to a screw conveyor which fills the wood chip bins. When the coal bunkering system is used for conveying wood chips, the grids will be removed from the vibrating screen in order to bypass the coal crusher.

The wood-chip bins are a live-bottom design which deliver, by means of one weigh-feeder per boiler, to a penumatic spreader on the preferential bed, of the associated boiler, as will be described later.

D. Ash Handling

A comprehensive system of ash handling is provided for the collection and storage of spent limestone and ash rejected from the fluidized beds, together with fly ash collected in the baghouse filters. A pneumatic eduction system is used wherein a steam exhauster provides the vacuum. A steam exhauster was selected over a motor-driven unit to reduce the requirement for electrical power.

An ash silo is provided to store the ash from 68 h of operation at maximum demand. This deviation from the 96 h requirement set for coal and limestone storage, to avoid haulage on weekends or during bad weather, was necessary to keep the height of the ash silo below aircraft flight interference plane.

Boiler and Furnace Design

A typical cross-section of the unit is illustrated in Figure 3. The boiler furnace and pressure parts are suitable for shop manufacture as a package and are an adaptation of a well-proven two-drum water-tube steam generator utilizing natural circulation throughout. The dimensions of the boiler package are such that it can be shipped by rail on a large, flat-bed rail car.

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The furnace differs from that of a conventional coal or oil-fired boiler, not only in the provision for a fluidized bed at the bottom, but also in that it is divided vertically by a membrane wall of tubes extending the full height of the furnace. This divides the bed into two sections arranged side by side parallel to the boiler drums. The bed closest to the drums is referred to as the preferential bed. It is in use whenever the boiler is in operation and it is the bed in which combustion is initiated by a lighting-up burner using No. 2 fuel oil. The preferential bed contains no heat exchange surface other than the membrane walls which form it. It requires virtually no refractory. In addition to coal it receives all the wood chips to be burned, the re-cycled fines from the convection bank and fly ash from the mechanical dust collector.

The other bed, which is slightly larger, is called the secondary bed. It operates at a somewhat lower temperature than the preferential bed, and incorporates immersed heat transfer surface in the form of inclined tubes passing through it. As with the membrane walls these tubes are cooled by natural circulation.

Combustion air is introduced through a large number of stainless-steel bubble caps penetrating the uncooled distributor plates which form the floor of the furnace. The bubble caps project above the distributor plates by a few centimetres and thus leave a layer of undisturbed bed material which serves as insulation. Each bed section is supplied with air from a separately-controlled plenum.

A spreader stoker is provided for each of the two beds. These distribute the coal along the length of the fluidized beds, that is parallel to the boiler drums. With conventional boiler firing the spreader stoker, with its incorporated chain feeder, meters or controls the rate of coal discharge into the furnace, but with the fluidized bed boilers the stokers will be set to give the optimum coal distribution across the beds, and metering of the coal to suit steam demand will be carried out upstream by means of weigh feeders. Incorporated in the spreader stoker which supplies the preferential bed is a water-cooled wood-feeding spout which injects wood chips by a combination of air jets and gravity. Wood is fed to the preferential bed only.

The limestone is admitted to each bed by a drop pipe at the end of the bed remote from the coal feeder. The drop pipe terminates at approximately the upper level of an expanded bed. The bed drains, on the other hand, are located at the coal feeder ends of the beds. Hence the limestone must traverse the entire length of the bed before reaching the discharge, thereby maximizing the residence time available for reaction. The limestone feed rate is controlled by weigh feeders upstream from the drop pipes.

The furnace cavity is tall, (approximately 8 m) and the flue gases leave at the highest point to enter the convective heat transfer zone of the boiler. The tall furnace is expected to facilitate completion of combustion and neutralization reactions as well as heat transfer.

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Additional boiler data, including predicted performance, are given in Table 6.

Carbon Recycle

The turbulent nature of the fluidized bed inevitably results in a carry-over of unburned carbon and limestone fines out of the furnace. Some of these will be deposited in the hopper beneath the two-pass convection section of the boiler. A much larger quantity will be trapped by the mechanical dust collector located between the boiler and the economizer. This carried-over material is re-injected into the preferential bed a short distance above the air distributor plate. The two streams are handled separately. Those from the mechanical collector are re-injected batch-wise through double gate valves and hoppers. The latter system requires less power for operation than the continuously-operated eductors, but space and height limitations precluded its use under the boiler bank.

In addition to improving carbon burn-out, and therefore boiler efficiency, the recycle system is expected to improve limestone utilization.

Bed Drain System

The bed drain system serves the dual purposes of varying the bed level in each cell to suit changing load conditions and of removing largely spent limestone together with residual ash from the coal. As mentioned earlier the bed drain pipes are at the ends of the beds remote from the limestone supply pipes to give maximum residence time for the limestone. The bed drain pipes, one per bed, pass from the bed at the level of the air distributor plate down through the air inlet plenum to bed drain coolers located under the boilers.

The bed drain coolers, one per bed, are water-cooled twin-screw conveyors driven by direct-current controllable-speed motors. The boiler control system varies the rotational speed of the screws, and thus controls the rate of extraction and the bed level. In the interest of thermal economy the bed drain coolers are circulated with condensate which is taken from and returned to the main hotwell. Thus the heat given up in the bed drain coolers is returned to the boiler feedwater.

The bed residue expelled from the drain coolers passes into hoppers from which it is automatically transferred by the ash handling system to the ash storage silo for disposal.

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Secondary Heat Recovery and Flue Gas Clean-up

To meet the design requirements for a maximum stack temperature of 175°C an economizer is located downstream from the mechanical dust collector. It is of finned tube design and is fitted with a single soot blower.

Final gas clean-up with respect to particulates is accomplished by means of bag filters. Each boiler has a baghouse located downstream of the mechanical dust collector and economizer. Thus the baghouse needs only to contend with relatively cool gas, laden with fine particulates. Teflon-coated bags are arranged in 12 cells of 36 filter tubes each. Cleaning is achieved by shock pulsing a reverse air flow sequentially to each cell. The dislodged fly ash accumulates in the conical hoppers beneath the filter tubes, and is removed by the pneumatic ash handling system which also serves the bed drain coolers.

Boiler Control System

A centralized control philosophy has been adopted whereby the fluidized-bed boilers can be started up, operated and shut down from the control room. Certain operations which are only carried out on start-up or shut-down of the boilers or which normally function automatically, are controlled from local stations outside the control room. The existing stoker-fired boilers are supervised from the control room but are started up and shut down from control centres local to the boilers.

Control of the boiler feedwater, air flow, coal and limestone feed, and bed level are provided by a Bailey Controls 820 Series electric analogue control system. All boiler control loops are regulated by means of Bailey operator control stations located on the panel.

The following loops are provided for each boiler:

1. Plant Master - to develop a demand for fuel and air flow for each boiler based on an indication of plant load. Header pressure is used as the demand signal.
2. Fuel Flow - to maintain fuel flow to the beds to suit load demand and air flow and to keep bed temperatures within allowable limits. Boiler master demand, air flow, fuel flow, bed temperature and oxygen in the flue gas are used to develop the control signal for each bed.
3. Air Flow - to maintain air flow in balance with load demand and fuel flow. The control signal for each bed is developed from boiler master demand, fuel flow, and oxygen in the flue gas.
4. Limestone Feed and Bed Drain - for each bed, to supply sufficient limestone and to control bed drain rate to maintain the bed level within prescribed limits. The limestone feed signal is developed from fuel flow, SO_2 in the flue gas, and limestone flow. The bed drain speed is regulated by a signal developed from bed level and limestone feed.

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5. Feedwater Flow - to maintain feedwater flow at the same rate as steam flow and to keep the level of water in the steam drum at the desired value. A two-element controller measuring steam flow and drum water level is used.

6. Miscellaneous Air Flows - to maintain the forced draft fan discharge pressure and primary air flow at the required level by control of the fan inlet vanes.

7. Furnace Pressure - to maintain the furnace pressure within a narrow band about a set-point value to ensure satisfactory combustion of fuel and safe unit operation. Total boiler air flow demand and furnace pressure are used to develop the signal which controls the inlet vanes of the induced draft fan.

8. Boiler Purge - to ensure that the ignition burner and the entire boiler are purged of all combustibles before a boiler start-up sequence is initiated.

Normally the foregoing loops are expected to function automatically, but the control stations also provide manual operation modes.

Materials Handling Control Systems

In general the material handling systems are designed to be operated from the control room. Exceptions to this are the filling of the wood bins, manual operation of isolating gates on the coal and limestone bunkers and bins, ash silo operation and coal and limestone receiving operations. All these functions are performed locally. No attempt has been made to integrate the fuel handling of the existing Plant No. 2 with that of the AFBC boilers.

Control panels are provided in the control room for the coal, limestone and ash handling systems. The coals and limestone handling systems both consist of two sub-systems. The first transports the material in question from the receiving hopper to the storage bunkers; the second transfers the material to the appropriate ready-use bin. Each system is operated from the corresponding panel in the control room, and mimic diagrams provide a convenient display of what is happening. The systems are conventional, but highly automated with interlocks and local trips.

The ash handling system can be operated entirely from the control room. The operator can manually select and unload any one of eight unloading stations, or he can program the controls to sequence automatically through the stations, in any order.

Present Status

At the beginning of September, 1982, mechanical erection of the plant was essentially complete, and installation of controls and instrumentation was progressing well. Materials handling systems and other mechanical auxiliaries have been tested, and boil-out of the boilers is scheduled to commence about mid-September. Acceptance tests are scheduled for December 1982 and January 1983.

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EMR plans an extensive series of performance evaluation trials which will commence after completion of the acceptance tests and will extend through the 1983/84 heating season. The program calls for testing of several coals, with and without co-firing of wood chips, measuring the effect of limestone size consist on sulphur capture, determining maximum rates of load pick-up and shedding, and measuring emissions under both steady-state and rapidly-changing load conditions.

STUDIES RELATED TO INDUSTRIAL COMBUSTORS AND BOILERS

Work in this area of EMR's FBC development program is generally of a short-term nature, aimed at specific potential applications. It usually consists of design studies or economic analyses co-sponsored with an industrial partner, technological expertise being obtained as necessary by sub-contract to appropriate suppliers. Two examples follow.

Combustion of Coal Washery Rejects for Coal Drying Applications

It has already been stated that coal up-grading operations produce several million tons of washery rejects per year, primarily in western Canada. Having a calorific value of about 10 MJ/kg (4,300 Btu/lb), these represent not only a disposal problem, but a low-quality energy source. A use for part of it lies at the source of supply, in the form of the heat requirement for coal drying, which is presently met with natural gas or cleaned coal. However, conventional technology is not able to cope with the high ash and moisture content of washery rejects.

In 1976 EMR, wishing to establish the suitability of FBC technology for burning washery rejects, contracted a short-term, pilot-scale study to Copeland Systems Inc. The test fuel was raw bituminous coal supplied by Luscar Ltd. from its Coal Valley mine in Alberta. When the raw coal at 18% ash was found to burn readily in the pilot-scale FBC, with no problems of sintering of slagging, it was mixed with fly ash to simulate washery rejects by raising the ash content first to 44%, then to 72%. The high ash material also burned readily, even when water equivalent to 10 wt% of the fuel was injected into the combustor. Details of the tests have already been reported (2).

These favourable results led EMR and Luscar Ltd. to collaborate, in 1980, in a more elaborate site-specific study. The objective was to determine the feasibility of using a large fluidized bed combustor burning washery rejects to provide heating requirements for coal drying and plant heating at the Coal Valley mine. The drying requirement is approximately 65 MW (220 million Btu/h) is presently supplied by propane-fired space heaters. The washery rejects contain about ten times this amount of energy, but in five different streams varying in size, ash content and moisture.

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Dorr Oliver Canada Ltd. were sub-contracted to prepare a process design and cost estimate. Of the design requirements they were required to address, the most important were as follows:

1. The existing PF furnace and burner system up-stream of the coal dryer were to be left intact, to be usable on a standby basis.
2. The hot gases entering the dryer from the FBC were to be no higher in ash content than the gases supplied by the existing PF system.
3. The coal dryer was to have the same turndown capability with the FBC system as with the existing system; that is 4:1.

Door-Oliver's scope of supply included making a recommendation as to which reject stream should be used to fuel the FBC. After a series of pilot-scale tests conducted with a 0.3 m combustor at Springdale, Conn., Door-Oliver identified the reject stream from the heavy media cyclones as the preferred fuel. It typically has the following characteristics:

Moisture:	15 - 20%
Ash, (dry basis):	65%
HHV, (dry basis):	11 MJ/kg (4,700 Btu/lb)
Size consist:	13 mm x 28 mesh

This stream is large enough to provide all the energy requirements for drying and heating, the size consist permits direct feed to the combustor without further preparation, and the moisture content is low enough to produce a low-humidity flue gas for efficient drying.

The combustion process design was developed around a single-compartment, cold-windbox, refractory-lined FBC approximately 7 m in diameter, with an expanded freeboard section to reduce ash entrainment. Meeting the requirements for gas cleanliness and turndown, however, proved difficult. It was accomplished by a system of eighteen large, refractory-lined cyclones, arranged in three trains. The design also provided another, smaller fluidized bed to serve as an ash cooler.

The total cost of the proposed system, complete with building, material handling equipment, pollution control equipment and systems for largely automated operation, was estimated at about $22,000,000 Canadian. Luscar's economic analysis concluded that the capital cost could not be justified by projected savings and clean coal and propane. However, at preparation plants using natural gas as dryer fuel, or at plants still in the planning stage, the economics could be much more attractive.

A summary report on this study is being prepared.

Recirculating Fluidized Bed Combustion of Oil Sands Coke

By far the largest proportion of Canada's petroleum resources are in the form of heavy bitumen, of which the Athabasca oil sands are a well known example. Two large plants are presently in operation, surface-mining

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the deposits and extracting the bitumen from the sand by a washing process. In order to produce a synthetic crude transportable by existing pipelines and acceptable to existing refineries, the bitumen must subsequently be up-graded. This is accomplished by thermal cracking, resulting in a coke residue, the nature of which depends upon the coking process.

The newer and larger plant, operated by Syncrude Canada Ltd., which was commissioned in 1978 and has an output of 125,000 bbl/day of synthetic crude, utilizes fluid cokers. These produce upwards of 2000 tonnes/day of coke. It is rather intractable as a fuel, being high in sulphur, very low in volatiles, difficult to grind, and containing some carbon forms which are relatively unreactive. The coke is currently being stockpiled, since no established technology is available by which it can be burned to generate part of the plant's process steam requirements.

Fluidized bed combustion has been proposed as a promising technology for this application, since it offers convenient control of SO_2 emissions, provides ample residence time for unreactive fuels, and does not require pulverizing. However, Syncrude coke presents a problem of high elutriation in bubbling-bed FBC because its size consist is fine, typically 98% less than 2 mm and 75% less than 0.2 mm. This is not a problem with recirculating fluidized bed combustors (ARFBC) because they are designed to tolerate a high degree of entrainment and so can accept feedstocks of fine particles size.

Since ARFBC technology appeared to hold the greater promise of success, EMR sponsored a short series of exploratory combustion trials in the pilot-scale ARFBC at the Hans Ahlstrom Laboratory in Finland. Other participants were Syncrude Canada Ltd., who provided an 18-tonne sample of coke, and the Alberta Oil Sands Technology Research Authority, which arranged to obtain and ship the sample to Finland.

In view of the fact that there was no previous experience with the combustion of Syncrude coke in a fluidized bed, the test objectives were kept simple. Primary objectives were to determined;

a) the effect of bed temperature on combustion efficiency,

b) the level of limestone injection required to control SO_2 emissions, and;

c) the input conditions which would optimize both combustion efficiency and sulphur capture.

Secondary objectives were to establish typical levels of NO_x emissions and the fate of vanadium compounds in the coke. Gotland limestone from Sweden was used as the sulphur sorbent because it was readily available and its characteristics are known. Its mean particle size was about 0.08 mm.

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The tests demonstrated that Syncrude coke can be burned quite successfully in an ARFBC. Combustion efficiencies, based on the high heating value of the fuel, ranged from 95.8% to 99.0%, at bed temperature ranging from 820°C to 950°C. A total sulphur capture of 90% or better was readily achieved by limestone addition at Ca/S molar ratios ranging from 1.72 to 2.09. Increasing bed temperature was found to favour combustion efficiency, but a bed temperature of 900°C appeared to offer the best compromise between efficiency of combustion and efficiency of sulphur capture. Results also indicated that CaO, in the large quantities required for sulphur capture, is effective in capturing most of the vanadium in the fuel, particulary at bed temperatures of 890°C and higher.

A detailed account of this study has recently been published (3).

THE NSPC 10,000 h CORROSION TEST PROGRAM

Background

It was stated earlier that the sulphur-capture aspect of FBC is of most interest in Canada's Atlantic provinces, where high-sulphur coal forms the major fossil fuel resource. Over the past three years EMR has financially supported the Nova Scotia Power Commission (NSPC) in engineering studies which established the feasibility and identified the risks of installing a 150 Mwe AFBC boiler. One of the major risk areas, and the one probably requiring the longest time to resolve, lies in the selection of boiler tube metals for in-bed service at high temperatures. At present, performance data for a wide variety of alloys are available, but only for exposure times of 4500 h or less, whereas metallurgists generally agree that exposures of 10,000 h or more are necessary to permit reasonably confident extrapolation of long-term behaviour in operation.

In view of this situation, EMR and MSPC have entered into an agreement to carry out a corrosion test program in which the most promising boiler tube alloys will be exposed for periods up to 10,000 h. The representative corrosive/erosive environment will be provided by a pilot-scale FBC combustor, 1 m^2, to be located at Point Tupper, Nova Scotia.

Methodology

Extensive consultation with authorities in the field, including scientists from TVA and EPRI, supplemented by a review of published literature, led to a decision to adopt testing techniques already proven by other researchers which would produce results directly comparable to existing shorter-term data. It was also decided to limit the candidate tube materials to six, all approved by the ASME boiler code. These are SA-210-A1, SA-213-T11, SA-213-T22, SA-213-HT9, SA-213-TP304H, and SA-213-TP347H. These will be exposed in the temperature range 450°to 650°C, covering the duty spectrum from water-wall to superheater tubes. In addition, alloy 800 H will be used as a marker to help relate the results to existing data.

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Test probes one metre in length will be made up from tube segments approximately 50 mm diameter and 50 mm long, welded or threaded together. Each of six test locations in the bed will be occupied by a pair of tubes having impressed longitudinal temperature gradients from 450 to 550°C, and 550 to 650°C, respectively. A seventh pair of tubes will be exposed in the splash zone, while a single tube at the higher temperature gradient will be located in the convective pass. The tubes will be air-cooled, with temperature being controlled by individually modulating the air supply to each probe. The number of arrangement of test probes has been selected to permit a change-out schedule which provides samples exposed from 1000 to 10,000 h in 1000 h increments.

In addition, four multi-specimen probes will be submitted to the full bed temperatures of 850°C to evaluate alloys for uncooled hangers. The candidate hangar alloys include SA-213-TP347H, SA-213-TP310, HK40 and "Sandvik" MA 253. These will be exposed in two locations for periods of 1000, 3000, 6000, and 10,000 h.

Since knowledge of the partial pressure of oxygen is essential to an understanding of the high temperature oxidation and sulphidation mechanisms, provision is being made to map O_2 concentration throughout the bed and especially in the vicinity of the test specimens.

Project Organization and Status

The project is controlled by a management committee, consisting of representatives from both EMR and NSPC, which directs a project manager who has been appointed by NSPC. Detailed design and supply of the FBC combustor has been contracted to CE Canada Ltd. This firm is also making a financial contribution to the project. As of September 15, 1982, combustor design had been finalized and procurement of purchased items for the test facility had begun. Completion of erection and commissioning of the facility is scheduled for early summer of 1983. NSPC will then operate the facility for the duration of the materials exposure program, while matellurgical evaluation of the test specimens will be carried out by CANMET.

Completion of the project is scheduled for early 1986, at a cost of approximately $8,000,000 Canadian.

SUPPORTING LABORATORY RESEARCH

It is common misconception that the role of research and development is completed when a new technology reaches the stage of commercial utilization. In fact, the need for R & D usually continues as long as the technology is in use. In the case of FBC, each new fuel, each new sorbent and virtually every application will present new problems. EMR has accordingly deemed it appropriate to provide laboratory research facilities, not only to support the commercial-scale demonstrations already described, but to continue the work of optimizing the technology as it matures.

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Pilot-Scale Bubbling-Bed FBC Facilities

At present the most important of EMR's R & D facilities are two pilot-scale bubbling-bed combustors, one operated as part of an in-house program at CANMET in Ottawa (4), the other operated under contract by Queen's University in Kingston, Ontario. The combustors are identical, although there are some differences in ancillary equipment. The CANMET facility was put into service in 1981 to replace a smaller, less versatile apparatus; the Queen's facility was commissioned in 1982.

The CANMET facility consists of a combustor with a variable number of in-bed water-cooled tubes, a freeboard section with cooling coils at the top, a cyclone dust collector with means for fly ash recycle, a gas-to-air heat exchanger downstream from the dust collector, a baghouse, and a stack. To this are added fuel and sulphur sorbent feed systems, blowers to provide air for combustion and cooling, an induced draft fan, and comprehensive instrumentation. The orientation of these components is shown schematically in Figure 4.

The combustor and freeboard are approximately square in section (380 mm x 400 mm), fabricated from refractory brick with a steel casing, in nine sections, stacked one upon another to a height of about 4.8 m. This assembly is centre-supported, so that the windbox can be removed from below, giving convenient access to the distributor plate and the combustor shaft. The windbox is fabricated from mild steel with no lining, ie. a cold windbox. It is equipped with an explosion relief vent and has the air distributor fixed to the top of it. The distributor is fitted with 100 bubble caps arranged in a 35 mm x 38 mm rectangular pitch. Stainless steel bolts, drilled up the axes and cross-drilled under the heads, were used to make the bubble caps. With this configuration the bolt heads serve as shields to prevent bed material from sifting into the windbox.

The present air supply is capable of providing fluidizing velocities up to 4 m/s at the design firing rate of 1400 MJ/h when silica sand in the range of 0.85 to 1.70 mm is used as bed material. Fluidized bed depths of about 0.75 m can be maintained.

The amount of heat which must be removed from the bed to maintain a target bed temperature depends upon the moisture content of the fuel, the thermal input rate, the excess air level, and the desired bed temperature. If a combustor is to cope with a wide range of fuel quality and operating conditions, it must have a variable bed cooling surface. This is accomplished in the CANMET combustor by a pair of water-cooled bed-tube retainers, located one each on opposite sides of the active bed zone. Each retainer is penetrated by 48 guide sleeves arranged on an 81 mm triangular pitch through which straight sections of stainless steel pipe, 15.8 mm I.D. (½ in. nominal pipe size) can be passed. These are connected

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externally, by elbows and hoses, to flow-meters and a water supply line, in series or parallel circuits as desired. The cooling requirements can usually be met with 20 tubes or less, but the provision of 48 allows flexibility in vertical and horizontal spacing. This arrangement is also convenient for studying heat transfer rates, boiler tube corrosion, and the effects of immersed tubes on bubble growth in the bed. The guide sleeves can also be used as ports for measuring probes or fly ash reinjection. Unused sleeves are capped off with a blank insert to prevent the sleeve filling up with bed material.

The fuel and limestone feed system consists of several components. A coal hopper having a capacity of about 300 kg rests upon a weigh scale with electronic read-out. To the bottom of the hopper is fitted a metering screw operated by a variable-speed drive, which controls the coal feed rate. The metering screw terminates in a small transfer box from which the coal falls through a flexible tube into a water-cooled delivery screw, also operated by a variable-speed drive, which in turn injects the coal into the combustor through either one of two ports. One is located in the active bed zone, about 100 mm above the distributor, the other is located 1.2m above the distributor, and is normally in the freeboard region. The limestone hopper is similarly placed upon an electronic weigh scale and similarly has a variable-speed metering screw which delivers into the aforementioned transfer box. Thus coal and limestone feed rates can be varied independently, but the two streams are fed to the combustor by the same delivery screw. To prevent blowback, the coal and limestone hoppers have sealed lids with an air supply to maintain a slight positive pressure.

At the top of the combustor freeboard are two banks of serpentine coils, each consisting of 8 passes of 15.8 mm I.D. pipe, which reduce the flue gas temperature by 175 to 225°C. The gases are then ducted into a small multicyclone dust collector which has a hopper bottom terminating in a rotary air lock. Through it, cyclone products can be withdrawn into drums, or pneumatically reinjected into the active bed zone. Gases exiting the dust collector pass into a gas-to-air, shell-and-tube heat exchanger which reduces the flue gas temperature to about 120°C, then into a small bag filter designed to remove all particles greater than 0.3 micron. The bag filter has an on-line bag cleaning system and means for discharging the collected fly ash into a closed container. A long vertical duct between the heat exchanger and the bag filter provides a location for isokinetic sampling to determine dust loading.

Instrumentation is conventional but extensive. Besides the weight scales from which coal and limstone feed rates can be determined, a calibrated orifice measures fluidizing air flow, a bank of rotameters measures the various water flows, while manometers and pressure transducers measure air and gas pressures. Concentrations of CO, CO_2, SO_2, O_2 and NO_x in the flue gas are continuously monitored by a bank of analysers. Much of the instrumentation output is recorded automatically by a datalogger. A mini-computer which will store the data, and, with suitable programming, carry out much of the data reduction, is on order.

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For the CANMET FBC facility, the program planned for the next few years has the objective of developing a bank of performance data on Canadian fuels which may utilize FBC technology, in order to reduce the risk in designing full-scale systems, and so expedite the application of the technology. To data, using the present combustor and its predecessor coke, a lignite from Ontario, two oxidized bituminous coals from Alberta, a sub-bitumunous coal from Alberta, and 9% - sulphur coal from New Brunswick. In addition, an extensive study of the feedstocks for the CFB Summerside project, to investigate the effects of limestone size consist, has just been completed. Some of this work has already been reported (5,6). The twin facility at Queen's University is presently contracted to evaluate the performance of several eastern Canadian limestone as sulphur sorbents for high-sulphur bituminous coals. The first test program at Queen's University is presently under way.

Bench-Scale Activities

At present two aspects of fluidized-bed combustion are being investigated on a bench scale at EMR's CANMET laboratories.

One is a sorbent utilization study, which has the objectives of investigating the physical and chemical reactions involved in sulphur capture, and exploring techniques to improve the efficiency of limestone utilization. A small, externally-heated fluidized bed has been built and a procedure has been developed whereby simulated flue gases containing a known concentration of SO_2 are passed through a fluidized bed of limestone, while SO_2 in the off-gas is continuously monitored. Any difference between the inlet and outlet SO_2 concentrations is due to absorption by the limestone and by comparing plots of concentration versus time, limestone can be ranked against one another in terms of reactivity. To date, about two dozen limestones from various parts of Canada have been tested in this way, some in several different size consists. This work is supplemented by contracts to other laboratories for similar evaluations and thermogravimetric analysis.

The other bench-scale study has the objective of developing apparatus and procedures for ranking the relative reactivity of various coals when exposed to fluidized bed combustion. The present approach envisions injecting batch samples of coal into a small, externally-heated FBC, and monitoring the concentration of flue gas constituents with time, but the apparatus is still under development, so the concept has not yet been tested.

SUMMARY

Fluidized bed technology is believed to have a wide range of applications in Canada by which it could contribute significantly to the national goal of energy self-reliance. To expedite its implementation the federal government supports a broad program of research, development and demonstration. The first commercial demonstration of coal-fired FBC boilers in Canada, a two-boiler heating plant at Canadian Forces Base Summerside, will be undergoing acceptance testing by the end of 1982. As an important step toward realizing utility applications of AFBC, a 10,000 h program to investigate materials corrosion phenomena has been undertaken and is now in early phases of equipment construction. Site-specific design and

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economic studies, pilot-scale evaluations of specific fuels or equipment configurations, and investigations relating to other aspects of the technology, are supported by contracts and projects cost-shared with industrial partners. Additional support for development of the technology is provided by research, both bench-scale and pilot-scale, carried on in-house and through contracts. The present level of effort is expected to continue for the next few years, and is expected to bear fruit in the form of several full-scale installations by the end of the century.

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6. Anthony, E.J., Desai, D.L. and Friedrich, F.D. "Fluidized-Bed Combustion of Suncor Coke" Division Report ERP/ERL 81-27 (TR); Energy Research Laboratories, CANMET, Energy Mines and Resources Canada, Ottawa, Canada, August 1981

Table 1

Boiler specified capacity and operating conditions

Full load continuous capacity	18,000 kg/h (40,000 lb/h) of steam
Continuous efficient capability	4,000 kg/h (9,000 lb/h) of steam
Steam condition	99.9% dry saturated
Steam pressure	760 to 965 kPa (110 to 140 psig)
Feed water temperature	160°C (350°F) max.
Availability	Minimum of three months of continuous 24 hours-a-day operation
Schedule down-time	Maximum 60 days per year
Loading following capability	Adequate to meet normal variations in plant demand as identified from plant records
Emissions SO_2	2.96 kg/10^6 k. cal. heat unput (1.64 lb/10^6 BTU heat input)
Particulates	0.36 kg/10^6 k. cal. heat input (0.2 lb/10^6 BTU heat input)
Visible emissions	Opacity of gases emitted to ambient not to exceed 5% as determined by the Environmental Protection Service of Environment Canada

Table 2

Particulars of Design Coal

(Devco, Prince Mine)

Proximate Analysis		Dry Basis	Range
Moisture	%	0.0	0-10
Ash	%	19.3	16-22
Volatile matter	%	33.5	
Fixed Carbon (by difference)	%	47.2	
		100.0	

Ultimate Analysis		Dry Basis	Range
Carbon	%	64.2	
Hydrogen	%	4.0	
Sulphur	%	5.5	5-6
Nitrogen	%	1.0	
Ash	%	19.3	16-22
Oxygen (by difference)	%	6.0	
		100.0	

Calorific Value	Dry Basis	Range
MJ/kg, gross	26.7	23.2 - 27.7
BTU/lb, gross	11,500	9,970 - 11,900

Ash Fusion Temperature	Reducing
Initial	1175°C (2150°F)
Softening, spherical	1305°C (2380°F)
Softening, hemispherical	1355°C (2470°F)
Fluid	1375°C (2510°F)

Ash Analysis (Typical)

SiO_2	39.7%	Al_2O_3	25.5%	Fe_2O_3	27.0%
TiO_2	1.2%	P_2O_5	0.7%	CaO	1.0%
MgO	0.5%	SO_3	0.7%	Na_2O	2.7%
K_2O	2.3%				

Size Consist: 50 mm (2 in) x 0 with a maximum of 20% less than 0.6 mm (28 mesh)

Table 3

Particulars of Supplementary Fuel

(Wood Chips)

Ultimate Analysis		Dry Basis	Range
Carbon	%	49.5	
Hydrogen	%	6.0	
Oxygen	%	42.0	
Nitrogen	%	1.0	
Ash	%	1.5	0.5 - 3.0
Moisture	%	0.0	30 - 60
Calorific Value			
MJ/kg, gross		20.2	8.1 - 14.2 (as fired)
BTU/lb, gross		8700	2480 - 6090

The wood chips would be a mixture of hardwood and softwood from a tree chipper, giving a size consist of: - 25 mm (1 in) x 0 but including twigs up to 50 cm (20 in) long.

Table 4

Particulars of Demonstration Fuel

(Low Grade Coal and Washery Rejects)

Proximate Analysis		Calorific Value
Ash	40% max.	
Moisture	12% max.	MJ/kg, gross 20.2
Sulphur	9% max.	BTU/lb, gross 8700

Ash Fusion Temperature, Initial 1000°C (1832°F) min.

Size Consist: - 50 mm (2 in.) x 0 with a maximum of 40% less than 0.6 mm (28 mesh)

Table 5

Particulars of Design Limestone

(Havelock Lime Works Ltd., Havelock, N.B.)

	As Element, %	As Oxide, %
Loss on ignition at 985° (1800°F)	42.60	42.60
Si (SiO_2)	0.63	1.35
Al (Al_2O_3)	0.08	0.15
Fe (Fe_2O_3)	0.12	0.17
Ca (CaO)	39.52	55.33
Mg (MgO)	0.41	0.08
S	0.01	
TOTAL	83.37	100.28

Est. Ca present as CaO + Ca $(OH)_2$: 0.05%

Est. Mg present as MgO + Mg $(OH)_2$: 0.01%

Est. Ca present as $CaSO_4$, assuming all S present as $CaSO_4$: 0.17%

The above indicates the design limestone as being approximately 98% $CaCO_3$.

Table 6

Design and Performance Data for the FBC Boiler

		Per Boiler at 100% MCR
Steam Flow	kg/h	18150
Outlet Pressure	kPa	965
Outlet Temperature	^{o}C	182
Feed Water Temperature	^{o}C	104
Boiler Blowdown Rate	kg/h	250
Coal Feed Rate	kg/h	2210
Limestone Feed Rate	kg/h	1019
Combustion Air Flow	kg/h	21150
Total Air Side Loss	mmH$_2$O	1455
Total Gas Side Loss	mmH$_2$O	310
Particulate Emissions	kg/10^6k.cal.	0.216
SO$_2$ Emissions	kg/10^6k.cal.	2.52
NO$_x$ Emissions	kg/10^6k cal.	2.16
Stack Temperature	^{o}C	176
Boiler Efficiency (ASME)	%	81.6
F.D. Fan H.P.		221
I.D. Fan H.P.		92.8
Excess Air	%	22
Turndown Ratio:		4.5:1*

	Pref. Bed	Sec. Bed
Bed Dimensions, m:	1.23x2.88	1.39x2.88
Operating Temp, ^{o}C:	885	830
Fluidizing Velocity, m/s:	2.4	3.0
Excess Air, %:	25	20
Ca/S Ratio:	3:1	3:1
Expanded Depth, m:	1.37	1.37

* With preferential bed only in service.

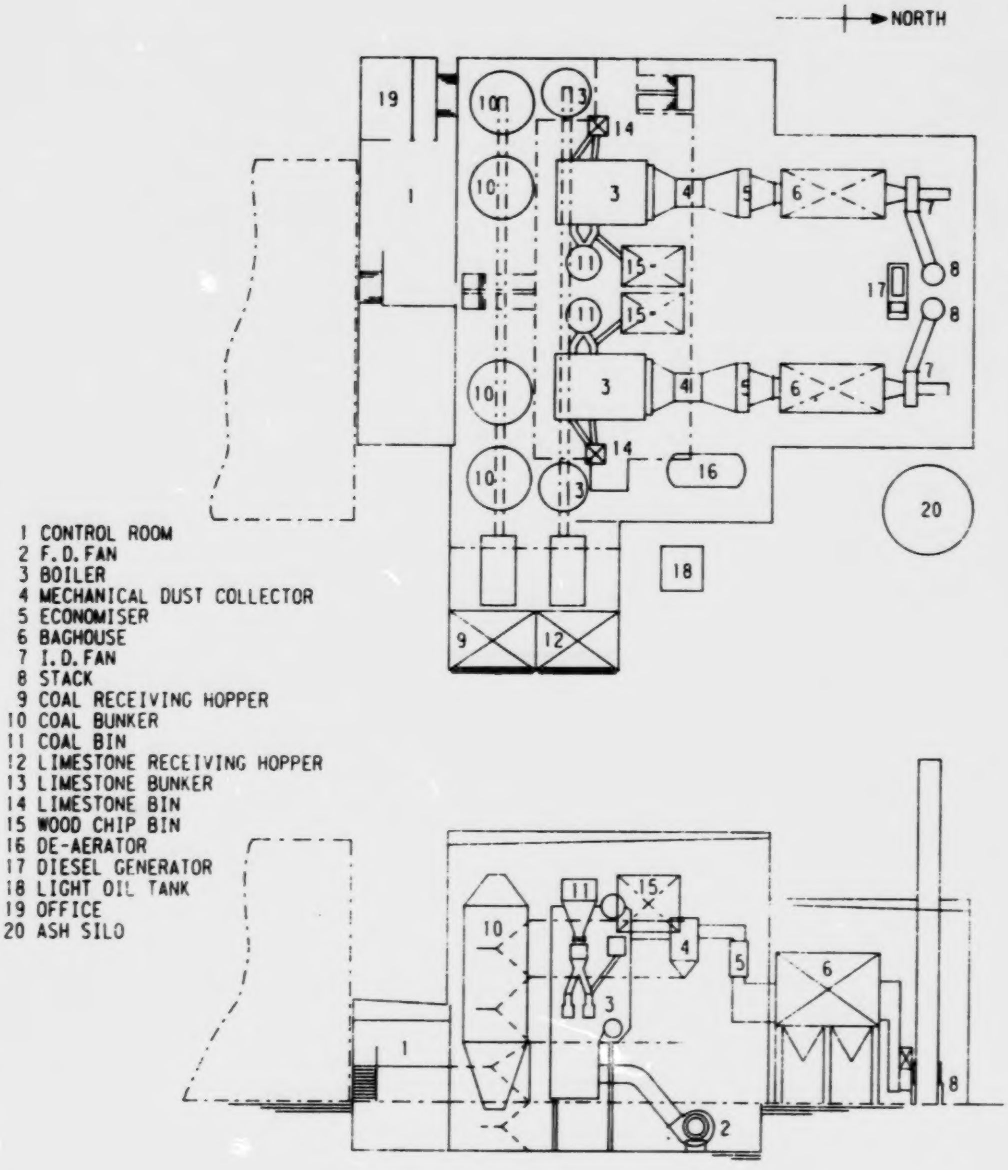
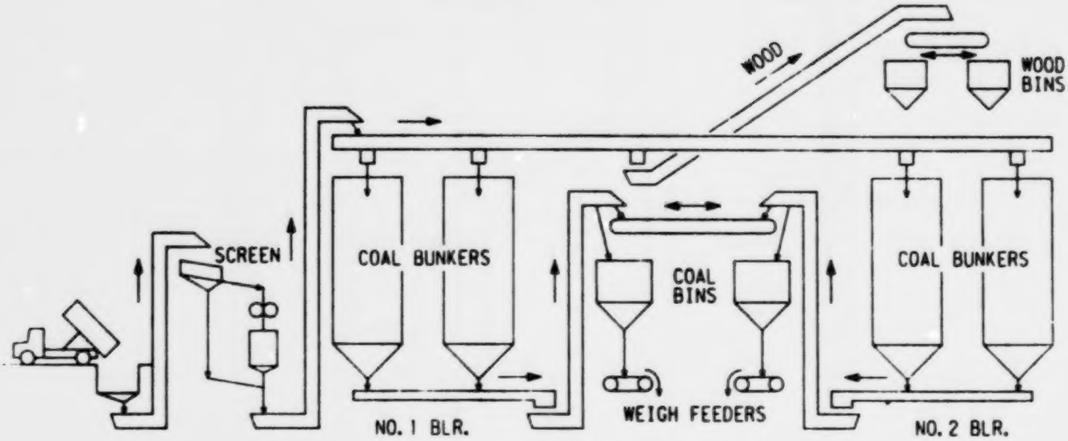
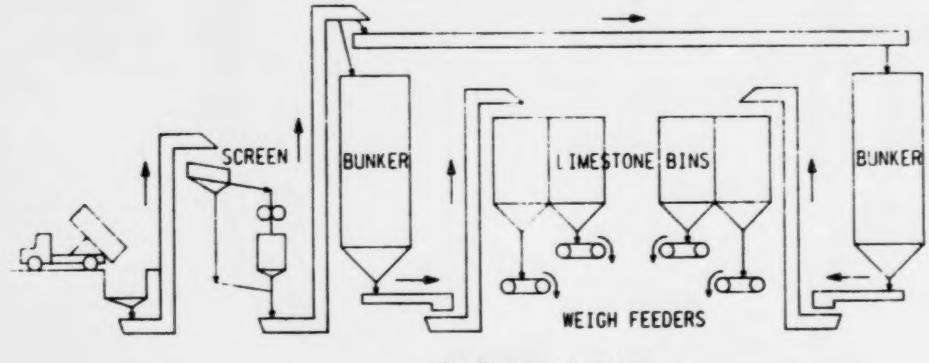

NORTH
19
10
13
14
1
3
4
5
6
7
8
11
15
17
16
20
18
9
12
2
1 CONTROL ROOM
2 F.D.FAN
3 BOILER
4 MECHANICAL DUST COLLECTOR
5 ECONOMISER
6 BAGHOUSE
7 I.D.FAN
8 STACK
9 COAL RECEIVING HOPPER
10 COAL BUNKER
11 COAL BIN
12 LIMESTONE RECEIVING HOPPER
13 LIMESTONE BUNKER
14 LIMESTONE BIN
15 WOOD CHIP BIN
16 DE-AERATOR
17 DIESEL GENERATOR
18 LIGHT OIL TANK
19 OFFICE
20 ASH SILO

Fig. 1 - Layout of the CFB Summerside FBC Boiler Plant


WOOD
WOOD BINS
SCREEN
COAL BUNKERS
COAL BINS
COAL BUNKERS
WEIGH FEEDERS
NO. 1 BLR.
NO. 2 BLR.

Flow Diagram - Coal and Wood


SCREEN
BUNKER
LIMESTONE BINS
BUNKER
WEIGH FEEDERS

Flow Diagram - Limestone

MATERIALS HANDLING - RATES AND CAPACITIES

	COAL	LIMESTONE
Transfer receiving hoppers to bunkers	6.3 kg/s (25TPH)	6.3 kg/s (25TPH)
Bunkers - capacity	4 x 74.8 Mg (82.5 T)	2 x 68 Mg (75 T)
Transfer to Bins	1.3 kg/s (5 TPH)	0.63 kg/s (2.5TPH)
Bins - Capacity	2 x 4.5 Mg (5 T)	2 x 2.3 Mg (2.5 T)
Burn rate	0.65 kg/s (2.5TPH)	0.3 kg/s (1.13TPH)

Fig. 2 - Flow Diagrams for the Coal, Wood and Limestone Storage and Handling Systems at the CFB Summerside FBC Boiler Plant

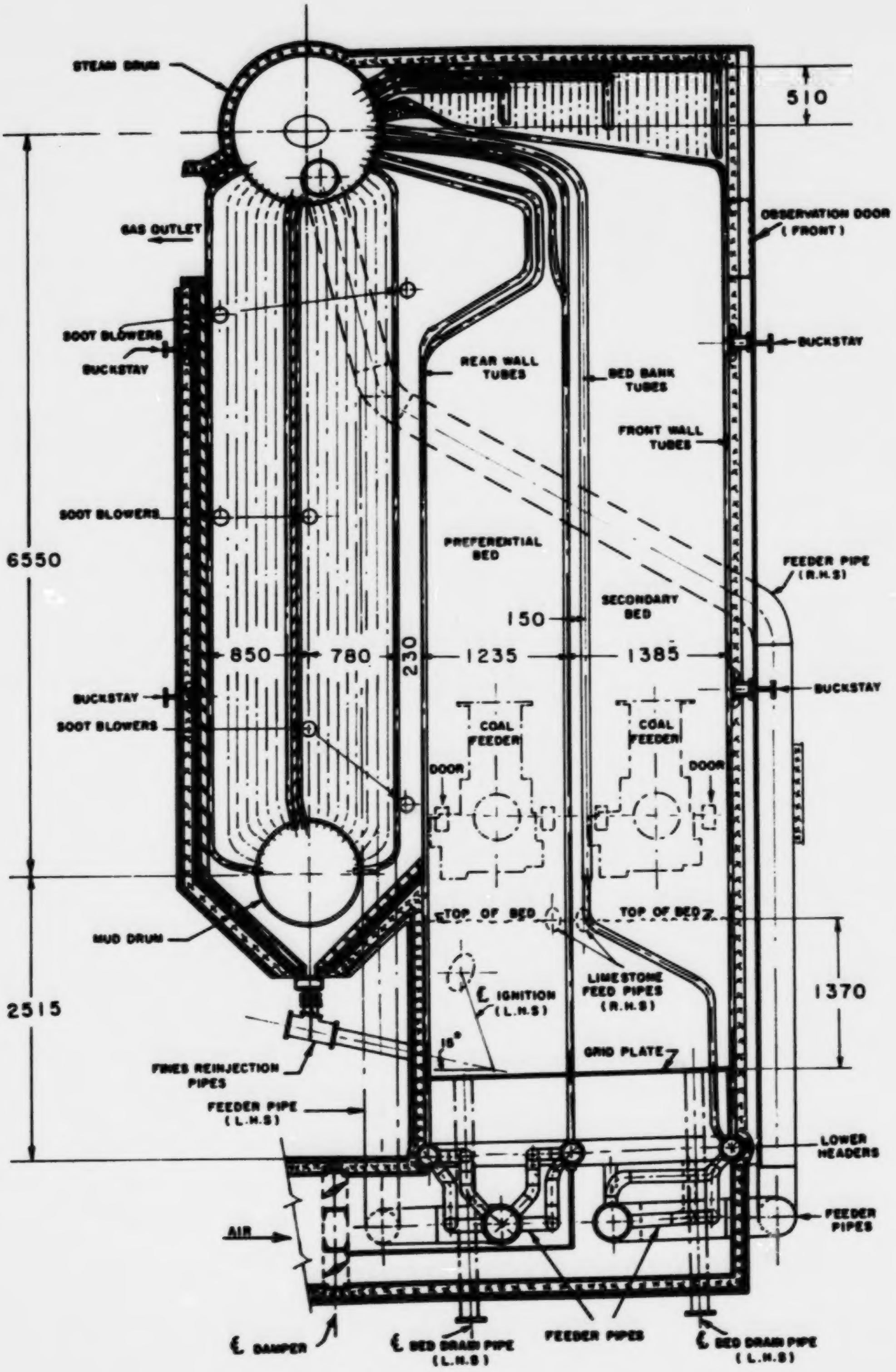

STEAM DRUM
510
GAS OUTLET
OBSERVATION DOOR (FRONT)
SOOT BLOWERS
BUCKSTAY
BUCKSTAY
REAR WALL TUBES
BED BANK TUBES
FRONT WALL TUBES
SOOT BLOWERS
6550
PREFERENTIAL BED
FEEDER PIPE (R.H.S)
SECONDARY BED
150
850
780
230
1235
1385
BUCKSTAY
BUCKSTAY
SOOT BLOWERS
COAL FEEDER
COAL FEEDER
DOOR
DOOR
MUD DRUM
TOP OF BED
TOP OF BED
LIMESTONE FEED PIPES (R.H.S)
1370
2515
℄ IGNITION (L.H.S)
18°
GRID PLATE
FINES REINJECTION PIPES
FEEDER PIPE (L.H.S)
LOWER HEADERS
AIR
FEEDER PIPES
℄ DAMPER
℄ BED DRAIN PIPE (L.H.S)
FEEDER PIPES
℄ BED DRAIN PIPE (L.H.S)

Fig. 3 - Cross-section view of the FBC Boilers at CFB Summerside
(Dimensions in millimetres)

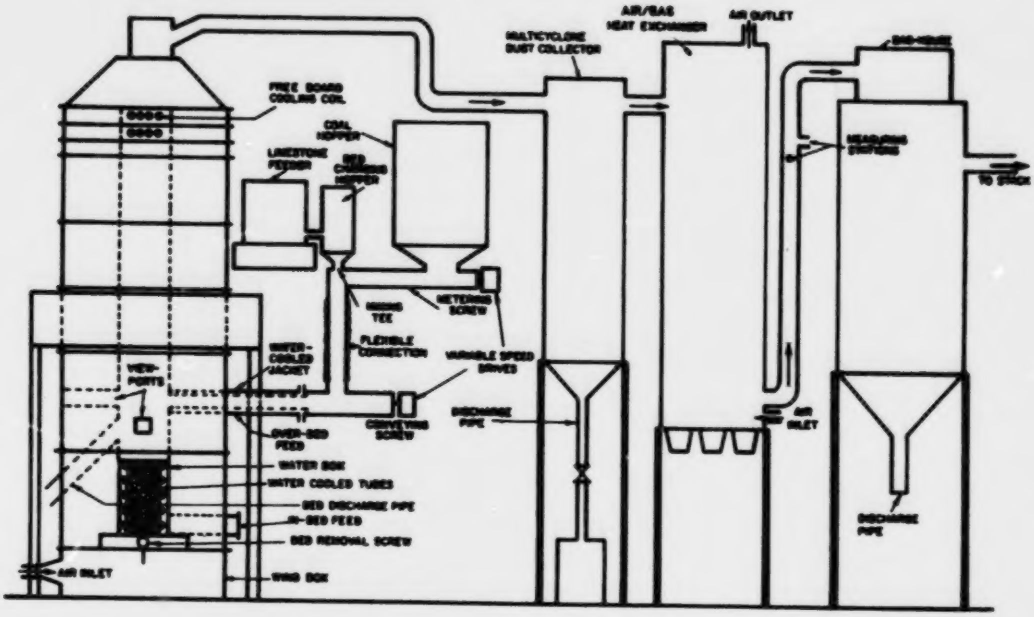

FREE BOARD COOLING COIL
COAL HOPPER
LIMESTONE FEEDER
BED CHARGING HOPPER
MIXING TEE
METERING SCREW
FLEXIBLE CONNECTION
VARIABLE SPEED DRIVES
WATER-COOLED JACKET
VIEW-PORTS
OVER-BED FEED
CONVEYING SCREW
DISCHARGE PIPE
WATER BOX
WATER COOLED TUBES
BED DISCHARGE PIPE
IN-BED FEED
BED REMOVAL SCREW
AIR INLET
WIND BOX
MULTICYCLONE DUST COLLECTOR
AIR/GAS HEAT EXCHANGER
AIR OUTLET
BAG-HOUSE
MEASURING STATIONS
TO STACK
AIR INLET
DISCHARGE PIPE

Fig. 4 - Schematic of the Pilot-scale Bubbling bed FBC at the CANMET Laboratories

ENERGY RECOVERY

FROM

WASHERY REJECTS

"NEW FUELS - NEW FIRING"
Canadian Institute of Energy
May 27, 1982

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The concept of utilizing a fluidized bed for high temperature reactions has grown from its initial use in catalyst recovery systems in the early 1940's to encompass a great number of industrial applications. The progression of development has been through roasting of gold-bearing pyrite ores, sewage sludge incineration, calcination of limestone and phosphate ores, drying miscellaneous materials, incineration of industrial wastes, and sulphate, partial, and reduction roasts of other metallurgical concentrates.

It has been amply demonstrated that the fluidized bed is a tremendously efficient gas-solid mixer, and that many gas-solid and gas-liquid reactions, especially at high temperature, can be carried out effectively in this medium.

In the combustion of organics, of course, there are ways other than fluidized bed which have been used for years, and may be simpler and less costly depending on the application itself. The oil burner and the grate-style boiler are examples.

What the fluidized bed has done is greatly expand the range of materials which can be utilized as energy sources, aside from simply providing a unique means of waste disposal.

In a simplified summary, the fluidized bed can be considered a specialized burner design, able to handle materials otherwise troublesome, uneconomical, or impossible to process.

Materials for which fluidized bed combustion is likely to be suitable could be solids or liquids, solutions or mixtures, and might exhibit one or more of the following characteristics:

1. Yields a non-combustible solid precipitate.
2. Produces a relatively low melting point residue.
3. Contains a high percentage of water.
4. Is of a sticky or very highly viscose nature.
5. Contains a substantial amount of non-combustible solid.

Examples of such materials are sewage and industrial sludges, biomass, peat, refinery waste, and coal tailings. Full sized fluidized bed systems are already well proven on some of these and others are the subject of much current testwork and discussion.

In its continuing work to develop proven and marketable fluid bed processing systems, Dorr-Oliver has been involved in much test and design work in the combustion of high sulphur coals and of coal tailings in the past five years. This lead naturally to an interest in other similar applications, and the opportunity to participate in a feasibility study for a major Western Canadian coal producer and Canmet in 1980 was welcome.

This coal washery uses an induced draft fluidized bed coal dryer rated at over 800 TPH, and fired by pulverized product coal. At issue was the feasibility of using otherwise wasted washery rejects to fuel the drying system in place of the clean coal which could otherwise be sold as product. The sensible heat input for the drying system is approximately 220 MM BTU/H. It was further determined that a further 33 MM BTU/H is the current peak demand for propane fired plant heating, and waste heat utilization for this purpose would be of significant benefit.

The available waste fuel resource, the washery tailings, are available as five separate streams as shown in Table I. Each of these has its own characteristic ash, moisture, size, and heat value analysis.

At the outset of the study, a number of design constraints were agreed upon, as it was not practical to make the study all encompassing or totally definitive at the time. The agreed upon constraints were as follows:

1. The tailings combustor would produce a quenched hot gas for direct use by the drying system.
2. Because of the uncertain effect of flyash on clean coal product quality, the quenched hot gas from the combustor was not to contain more ash than currently present from the pulverizer combustion of clean coal.

3. Continuous turndown of the combustor output was to be provided, to follow the usual operating cycle of the drying system (220 MM BTU/H maximum, 55 MM BTU/H minimum), and the plant heating system (33 MM BTU/H maximum, 1.6 MM BTU/H minimum). This calculates to approximately 4.5 to 1.
4. The final ash was to be discharged from the system at 250°F maximum for trucking to land fill.
5. Minimum modification was to be made to the existing dryer equipment, controls, and operating characteristics. The existing pulverizer burners were to be retained for standby use.

An evaluation of the quantities available, and the calorific, chemical and size analysis of the principal waste streams provided sufficient information to select an appropriate "fuel" for FluoSolids Combustion lab tests. For this particular application it appeared that the 1/2" by 28 mesh heavy media cyclone rejects would be the most appropriate fraction to use for the following reasons:

1. No feed preparation was apparently necessary.
2. Moisture content is reasonably low, an important factor with respect to dewpoint in the cyclones of the drying system.
3. There was sufficient quantity available to meet the total heat requirements.
4. This material was available from a single bin and would not

require blending with any of the other reject materials in order to produce a suitable feed.

It should also be noted here that any of these available wastes, or a mixture of them, could be burned in a fluid bed system, as could run of mine ore. The coarser materials would require crushing, and the finer would need a larger combustion reactor chamber. The very wet wastes would yield far lower energy recovery, but even the 35% solids, 65% water thickener underflow will burn without supplemental fuel in a FluoSolids System with heat exchanger unit, and still produce some byproduct energy.

A comprehensive fluid bed test program was conducted at Dorr-Oliver's Stamford laboratories in a 12" dia. reactor. This program indicated a number of critical operating parameters including combustion efficiencies (in the 95 to 99% range), decrepitation of solids (approximately six screen sizes), and a clean final ash product having loss of ignition of about 3%. Exhaust gases were found to contain negligible amounts of combustibles, 0 to 50 PPM of SO_2, and in the area of 160 to 190 PPM of NO_x.

The conclusion was reached that this material was indeed suitable for FluoSolids combustion for energy recovery. The task of meeting the design constraints for the total system resulted in the flowsheet shown in Figure I.

A single reactor unit was selected, with a single fluidized bed and air supply, as the turndown of fluidizing air was found to be very close to the desired 4.5 to 1 ratio. The gas cleaning quality constraints proved to be the most serious mechanically as the hot gas volumes involved are very large and very large cyclones are inherently relatively inefficient machines. Three trains each with two stages of cyclones were proposed, with one train to be shutdown as turndown progresses in order to maintain velocity and efficiency in the others.

The continuous turndown available, as shown in the testwork, proved to be about 4 to 1, just short of the desired target. Partial defluidization of the bed was considered a possibility to solve this, but in this instance, partial waste of hot gases to a scrubber was selected as a simpler operating solution in order to attain the 4.5 to 1 ratio.

Hot gas quenching to the desired dryer inlet temperature was to be done by controlled air injection after the cyclones, and a thermal fluid heating system was to be added in a bypass on the product gas duct on its way to the dryer.

Hot quenched gases then proceed to the dryer airheater for direct use. Dryer control, rather than varying the pulverizer firing rate, now would set the airheater temperature, with the combustor control system responding with quenched air damper adjustment and further feed back to the rejects feed rate to the combustor. It was acknowledged that the firing rate response for the combustor is quite a bit slower than that of a pulverizer burner, and it was recognized that the dryer feed bin level would be required to become a more important factor in establishing the instantaneous drying rate for the plant.

Hot ash from the combustor unit would be continously discharged to a fluidized bed cooler and thence to ash load-out bins. A baghouse was selected for final dust capture in order to minimize pressure drop and water consumption. The available heat from this cooler was found to be insufficient for the building heating job and therefore no attempt was made to further scavenge this source.

Although direct use of hot combustion gases initially appeared to be the simplest approach, the fact remains that this can only be so if the entire drying operation can be run at a steady state. The risk of product contamination with ash and the turndown needs of a normal plant both contribute very substantially to the cost and space requirements for cyclones and ductwork in this particular case.

In review the above result, and drawing on some sewage incineration experience, we can see a significant opportunity for simplification of this system. It is obvious that the major operating drawback with direct use of hot combustion gases in the dryer is the fact that, for optimum operation, and indeed reasonable control, the dryer must now follow the more slowly responsive combustion system rather than the washery for which it is intended. The answer of course is to put the combustion system into an arrangement which makes it entirely independent of the balance of the plant. The flowsheet of Figure II portrays such a system.

In this arrangement the combustion system comprises a reactor vessel, a gas to air heat exchanger, an optional boiler, economizer or other second stage heat recovery unit, and final hot gas conditioning and/or cleaning and discharge. The primary heat exchanger can preheat air for the dryer to about 1000°F, just about exactly what the dryer requires, and this type of duty has been well proven in sewage sludge installations. Hot gas cleaning may not be required, depending on the size analysis of the fuel, and even if necessary, need not be of high efficiency. As long as provision is made to dump hot air when the dryer does not require it, the combustion system can operate entirely independently of the dryer.

After this initial heat exchanger, hot combustion gases are available in the area of 900°F, with sufficient energy for warm or hot air for other combustion systems, hot water or thermal fluids for heating, or for the manufacture of steam and possibly electricity generation. If a boiler is contemplated, bed coils may be added to the reactor itself in order to greatly increase the steam production, and improve the overall efficiency of the system. A wet scrubber can treat the final exhaust gases directly, or some additional conditioning would permit the use of an electrostatic precipitator or baghouse.

In the very simplest system, a single heat exchanger would be followed by a venturi scrubber. The hot ash discharge from the combustor itself can be cooled as before for hauling to landfill or for possible use as road bed material if it is of sufficient quality.

It is this latter flowsheet and equipment arrangement which I perceive to have the greatest possibilities in the immediate future for waste fuel firing of a coal dryer.

Where we go from here is relative simple. The process is proven, the equipment is available, and the applications in industry exist now. Favourable economics for a particular installation, weighing capital cost of such a combustion system against the continuing cost of gas, oil or product coal is the only thing required before we proceed to build the first full scale plant of this type.

TABLE 1

TAILING CHARACTERISTICS (TYPICAL)

Tailing	% Ash*	% Moisture	BTU/LB*
Wemco Drum	60	10	4,000
Heavy Media Cyclone	65	20	3,500
Spiral	30	40	8,250
Thickener	55	65 To 70	4,200

* Air Dry Basis

TABLE 2

HEAVY MEDIA CYCLONE REJECTS (AS TESTED)

Moisture : 12% (Wet Basis)
Ash : 67% (Dry Basis)
Fixed Carbon : 14% (Dry Basis)
Volatile : 18% (Dry Basis)
Sulphur : 0.15% (Dry Basis)
High Heat Valve: 2,900 BTU/LB (Dry Basis)

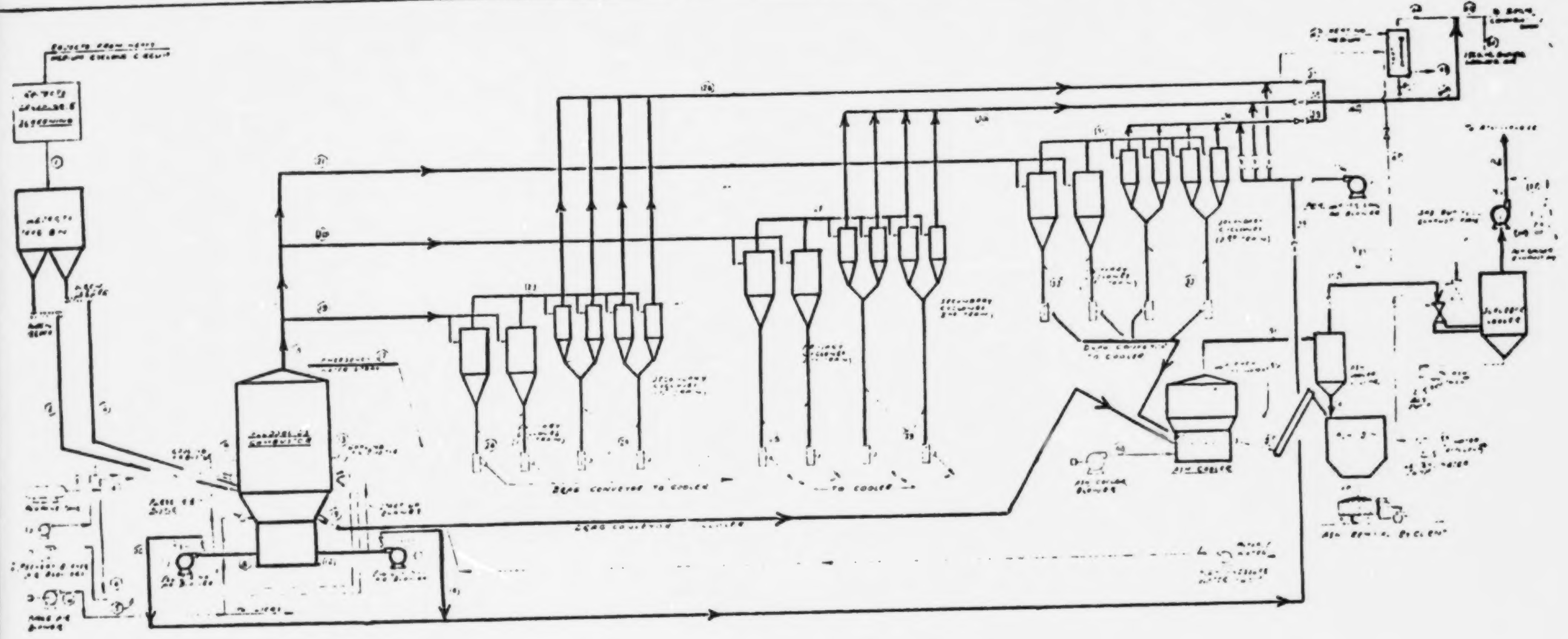

DRAG CONVEYOR TO COOLER
TO COOLER

FIGURE 1

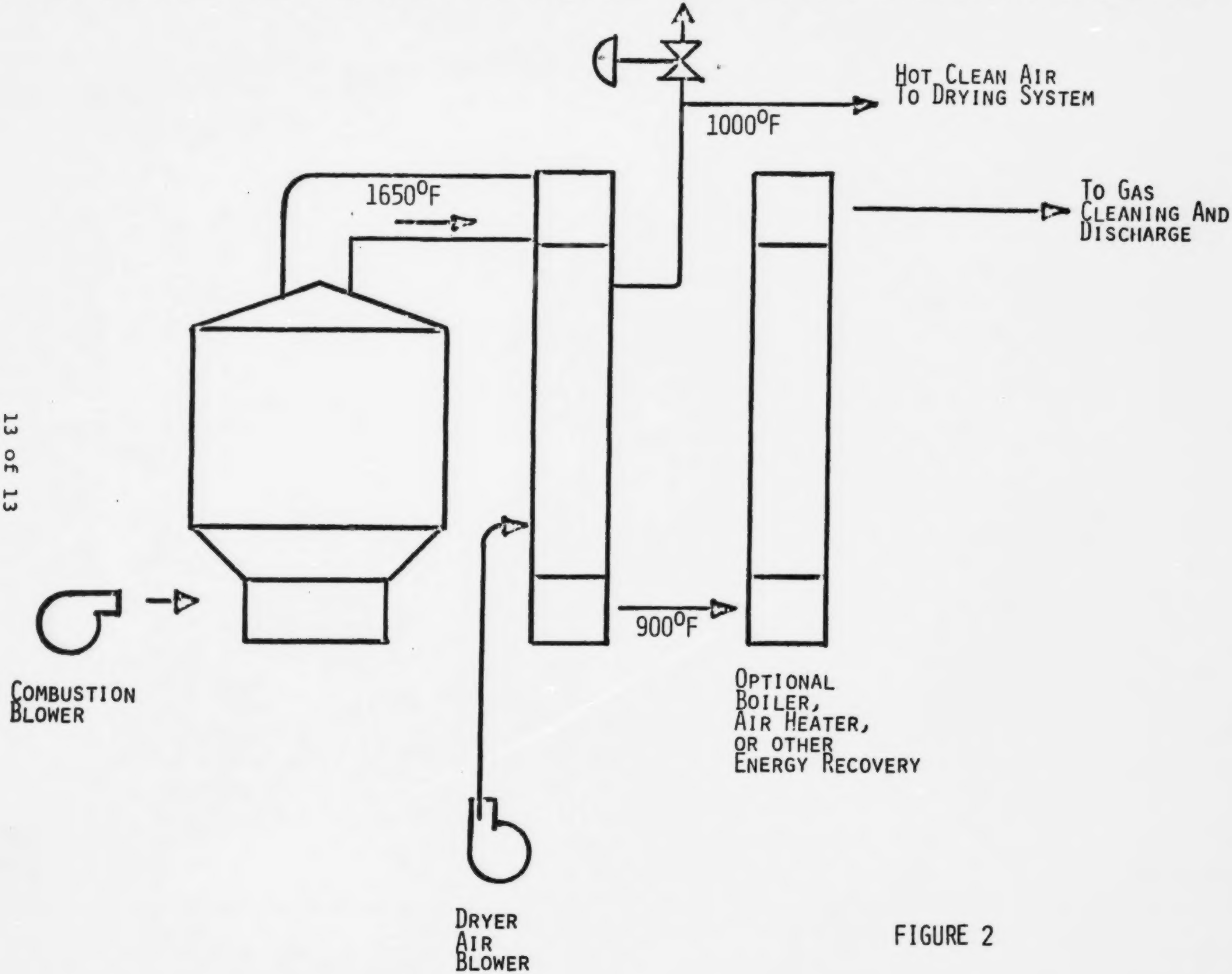
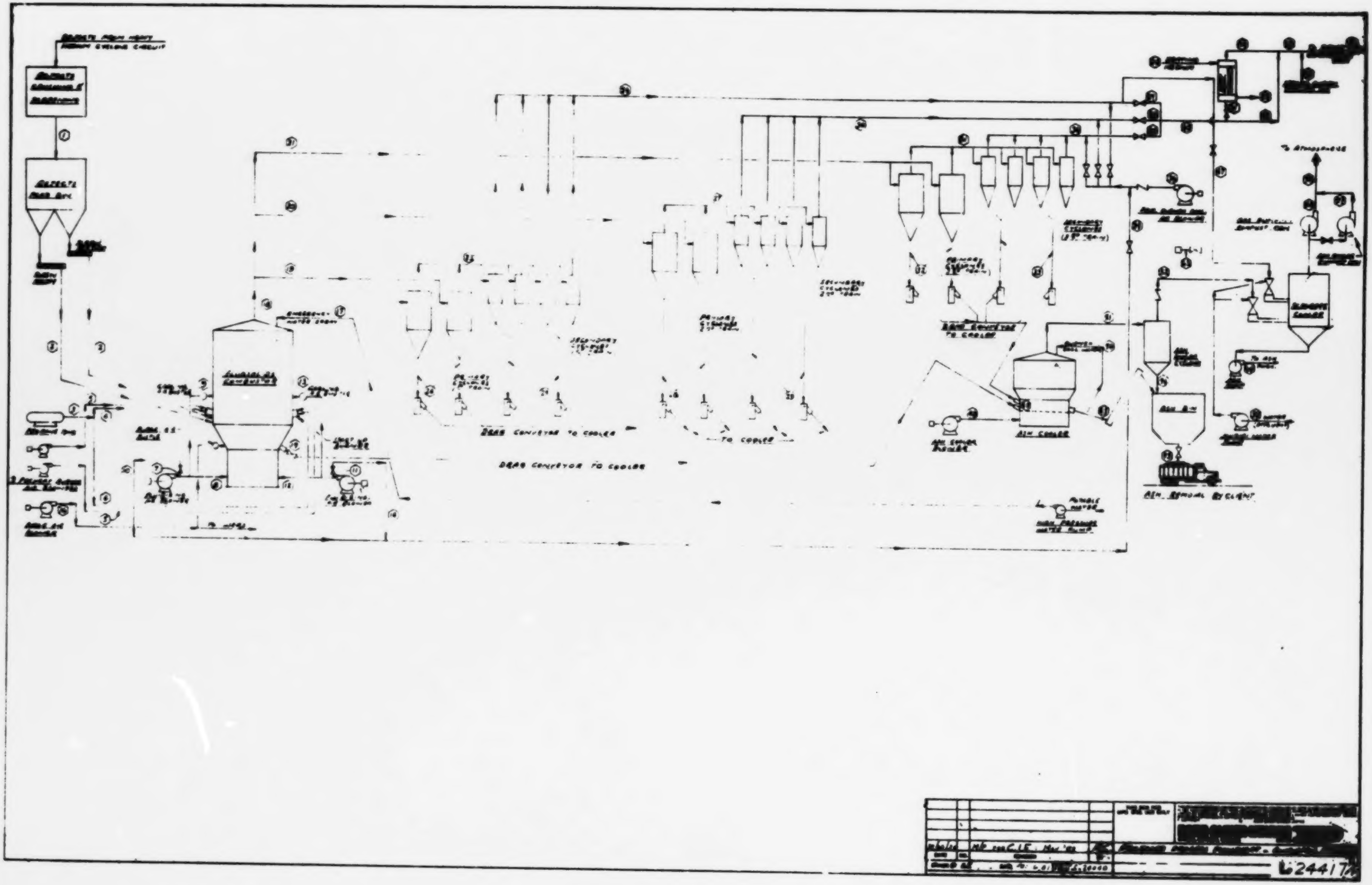

Hot Clean Air
To Drying System
1000°F
1650°F
To Gas
Cleaning And
Discharge
900°F
Combustion
Blower
Optional
Boiler,
Air Heater,
or other
Energy Recovery
Dryer
Air
Blower

FIGURE 2


DRAG CONVEYOR TO COOLER
DRAG CONVEYOR TO COOLER
TO COOLER
PRIMARY CYCLONES
SECONDARY CYCLONES
ASH CONVEYOR TO COOLER
ASH COOLER
ASH COOLER BLOWER
ASH BIN
ASH REMOVAL BY CLIENT
TO ATMOSPHERE
POTABLE WATER
HIGH PRESSURE WATER PUMP
L24417

UTILITY DEVELOPMENT OF ATMOSPHERIC FLUIDIZED BED COMBUSTION (AFBC) TECHNOLOGY IN THE UNITED STATES

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INTRODUCTION

Fluidized bed combustion (FBC) is an advanced coal burning process which provides a method of burning coal economically and in an environmentally acceptable manner. This technology stands to be a near-term alternative to the conventional pulverized coal (PC) steam plants which require a complex environmental control technology in order to meet emission standards. In principal, the AFBC process is very simple (Figure 1).

AFBC involves burning coal in a bed of limestone particles. Air passing through the bed from underneath suspends the coal/limestone mixture, turning it into a turbulent mass of hot, dry solids which closely resembles a boiling liquid. Sulfur dioxide, an undesirable by-product of burning coal, is captured by calcium oxide formed from the limestone to produce calcium sulfate as a by-product. Studies indicate that this dry, solid by-product may have useful applications or may at least provide a material which can be disposed of economically. Since the operating temperature of the fluidized bed is around 1550°F (843°C), roughly one half the temperature of a conventional coal-fired boiler, the formation of nitrogen oxides, a pollutant which is receiving increasing attention, is greatly reduced.

The AFBC process offers other advantages. The high heat transfer characteristics of boiler tubes within the fluidized bed reduce the physical size of the boiler and the surface area of expensive alloy tubing. Elimination of flue-gas scrubbing improves the overall plant efficiency and reduces plant cost. A major advantage of an AFBC boiler is its ability to burn a variety of fuel types without significant performance deterioration. This means that the large quantities of available low-rank coals can be successfully burned without the reliability problems associated with slagging or fouling in boilers. In summary, this results in a utility power plant that is potentially lower in capital and operating cost and is capable of meeting projected environmental standards.

STATUS OF AFBC TECHNOLOGY

Like many other coal technologies (fuel cells, synthetic fuels from coal, etc.), the concept of AFBC is not new. In the early 1920s a patent was sought for a device that could produce gas from coal. Today, there are hundreds of fluidized bed processes in use at chemical plants and oil refineries throughout the world.

In the 1970s, the thrust of utility AFBC research accelerated with a combination of bench-scale research, hot/cold modeling, and some pioneering successes. The United States Department of Energy (DOE) built the Rivesville 30-MW AFBC unit to demonstrate that AFBC could generate electricity.

The Rivesville AFBC design was initiated in late 1972, applying technology learned from the Pope, Evans and Robbins 0.5-MW bench-scale combustor located at Alexandria, Virginia. Rivesville represented an initial design of a multicell boiler to be used as a basis for a larger demonstration and utility-scale plant, and this was the first major step toward DOE's commercially-sized central-station power program. From operating experiences at Rivesville, we have learned that:

- An excessive in-bed heat transfer surface will limit turndown and can cause excessive bed cooling which quenches the fire. Scale-up of this data from very small units is inappropriate.

- High freeboards are needed to improve performance in sulfur capture, combustion efficiency, and sorbent utilization.

- Instrumentation and control flexibilities are necessary to control the process.

- Corrosion and erosion of boiler materials were not as severe as expected.

- Progressive startups of slumped beds can be successfully accomplished by transferring hot material from adjacent active beds.

- Pilot plant designs must include flexibility to test optional design features and changes to auxiliary systems. For example, several failures of the coal-feed system occurred before a workable solution was found.

- Pilot plant and demonstration facilities must be independent of other operating units. For example, failures of the host utility's boiler, upon which the Rivesville unit was dependent, also forced the AFBC test facility to shut down.

- Subdividing a pneumatically-conveyed flow of solids against the back pressure of an AFBC is essentially new and critical feeding technology.

Even though funding restraints prohibited the inclusion of many desired features, the Rivesville AFBC boiler achieved more than 800 h of commercial steam supply at a maximum rate of 187,000 lb (84,822 kg)/h to the host utility's turbogenerator.

A significant advancement over the Rivesville experience was the Electric Power Research Institute (EPRI)/Babcock & Wilcox (B&W) 6 ft x 6 ft (1.83 m x 1.83 m) AFBC unit. This unit included design changes and provided much needed operating and performance data.

Results from the 6 ft x 6 ft AFBC unit led to installing higher freeboards for longer combustion and reaction times and to the recycling of unburned carbon and unreacted or partially reacted limestone elutriants; hence, separate carbon burnup beds could be eliminated. Even with the success of this unit, it became readily apparent that a larger plant having the capability of retrofitting design changes was needed to test new hardware and to resolve uncertainties.

Performance of the AFBC process over the last few years has shown marked improvements (Figures 2 and 3). The significant technology development these improvements can be attributed to is recycle of elutriated material from the combustor. For 90-percent sulfur removal, the technology has progressed from a predicted calcium-to-sulfur ratio of about 5.0 (4.5 for 85-percent removal) in early 1977 to a ratio of close to 2.0 today. The predicted ratio for TVA's pilot is 2.0.

Similar improvements in nitrogen oxide emissions have also been observed. The Rivesville design basis showed 0.6 lb of NO_x (0.257 kg/GJ) per MBtu in early 1977. Current data from the EPRI/B&W 6 ft x6 ft AFBC unit indicates that 0.2 lb/MBtu's (0.086 kg/GJ), or better, is possible. The predicted level in the 20-MW pilot plant is less than 0.3 lb/MBtu (0.129 kb/GJ).

Carbon utilization has also been improved over the years. Studies in the mid 1970s indicated that only about 89-percent carbon utilization was achieveable in the main combustor. Recent results from the EPRI/B&W 6 ft x 6 ft AFBC unit indicate that 99-percent carbon utilization is achieveable in the main combustor. The predicted level for the 20-MW pilot plant is around 99-percent carbon utilization.

TVA'S HISTORY IN FLUIDIZED BED COMBUSTION

In mid 1975, TVA participated with the Environmental Protection Agency in the Energy Conversion and Alternatives Study, which was conducted to compare the economic and performance characteristics of conventional PC-fired steam plants with flue-gas desulfurization (scrubbers), AFBC power plants, and pressurized FBC power plants. A final report was published in November 1977.

Developmental activities began in earnest in September 1976 when the TVA Board of Directors authorized $4 million to prepare a preliminary conceptual design of a demonstration plant and to perform technical support research projects. TVA purchased preliminary designs from Combustion Engineering, Foster-Wheeler, and B&W. TVA also purchased a conceptual design and study of the pilot plant from B&W. The demonstration plant preliminary designs were funded by both TVA and DOE and were completed in November 1978.

A number of small-scale AFBC development units, which have been built and operated, continue to confirm the attractiveness of this technology. None of these, however, answer the many engineering design and operating questions which must be resolved before this technology can be used in a larger-scale utility plant, and nor do they permit assessment of the full environmental impact of this technology. In September 1979, TVA committed to purchase a 20-MW AFBC pilot plant in order to provide design confidence and the flexibility to test process improvements along with emission controls. A turn-key contract was subsequently placed with B&W for this facility.

Also in September 1979, final conceptual designs and cost estimates for a 200-MW AFBC demonstration plant were initiated by contracts with three major suppliers of utility steam generation equipment.

TVA's 20-MW AFBC PILOT PLANT - FACILITY

A project team, needed to carry forward the design, erection, and operation of the 20-MW AFBC pilot plant, was assembled. A concerted effort was made to utilize available expertise and to learn from past and ongoing FBC activities.

The pilot plant project is composed of a facility phase and a test program phase. The facility was built by B&W and Stone & Webster (S&W) under a contract with TVA. The technical staff at EPRI provided a review and consultation service on the facility design. A test program for operating the 20-MW AFBC pilot plant under a cosponsored contract between TVA and EPRI has been planned and is being implemented. TVA will operate the facility, assist in the development of the test plan, analyze and interpret the data, and perform other activities related to the operational testing of the pilot plant.

The 20-MW AFBC pilot plant has been designed with a great deal of flexibility in order to reach the following major goals:

- Prove that efficient and cost-effective performance of an AFBC boiler and auxiliary systems can be obtained under utility operating conditions and to facilitate the rapid development of this technology.

- Develop and prove-out operating control schemes required for reliable utility performance relative to variations in power demand (i.e., load following operations).
- Test, compare, develop, evaluate, and select large-scale auxiliary components and AFBC facility design configurations.
- Demonstrate adequate emission controls and combustion efficiency over a range of alternate process and equipment configurations.
- Evaluate and/or develop the necessary predictive modeling tools to enable correlation of test results for use in designing larger AFBC utility units with confidence.
- Establish a data base for a range of coals and limestones to enable scale-up of AFBC to commercial size for a range of applications.

Work on the pilot plant has been actively proceeding for the past two and one-half years. The facility, now constructed, is located at TVA's Shawnee Steam Plant near Paducah, Kentucky. Site preparation and initial construction began in April 1980. Operation of the facility was initiated in May 1982. Schedules for the facility and test program phases are shown in Figures 4 and 5.

The pilot plant has been designed to test various mechanical subsystems and to optimize parameters for good performance and reliability under utility operating condtions. A cutaway view of the facility is shown in Figure 6. The pilot plant will allow testing of various feed systems (overbed and underbed), fluidizing velocities of 4, 8, and 12 ft/s (1.2, 2.4, and 3.7 m/s), control and load following techniques, and various environmental control techniques. The fluidized bed will contain 216 ft^2 (20 m^2) of active area, 12 ft x 18 ft (3.7 m x 5.5 m) plus 72 ft^2 (6.7 m^2) 6 ft x 12 ft (1.8 m x 3.7 m) of area, which will be started using oil before converting to coal feed. The active area (separates into four regions) is progressively lighted from the startup area and does not require the use of oil. The steam conditions are 2400 psig and 1000°F (16,546 kPa and 538°C).

The nominal design conditions are 8 ft/s (2.4 m/s) fluidizing velocity, 4 ft (1.2 m) bed depth (with provision for 4 ft to 6 ft (1.2 m to 1.8 m) and 843°C in-bed temperature (with provision for 1400°F to 1700°F (760°C to 927°C). The design incorporates:

- Recycle of char to the main bed (the carbon burn-up bed was deleted from the design).
- A feed point spacing of 1 per 18 ft^2 (1.7 m^2), with provisions for 1 per 9 ft^2 (0.8 m^2) or 1 per 27 ft^2 (2.5 m^2).
- A water-cooled bubble-cap distributor plate.

- A combustor designed for a 2-second gas pass residence time.
- A direct digital computer control/data acquisition system.

A number of technical areas of concern need to be resolved from the operation of the AFBC pilot plant. These include the following:

Coal/Limestone Distribution

Several alternate feed systems will be tested. Included are an overbed stoker feed system with separate overbed limestone feed and an underbed pneumatic feed system for coal and limestone. The distribution of coal and limestone to the fluid bed has been a primary area of concern. Information proving that a feed system can be designed which is reliable and durable enough for utility-type operation is needed. Conveying line design, allowable velocities with respect to moisture and erosion, splitting effectiveness, and feed nozzle design are among the items which must be better understood and optimized. These will be addressed in the pilot plant and in the coal/limestone feed test facility.

Boiler Construction Materials

Previous research and testing has indicated that standard materials used in fossil power plants will perform satisfactorily in an AFBC boiler. However, coal/limestone distribution, system control and operation, and bed performance could produce localized reducing conditions which might impact the long-term performance of boiler materials. Testing during pilot plant operation will address these potential problems.

Erosion

To achieve acceptable bed performance, recycle of elutriated fine particles back to the main bed will be needed in an AFBC boiler. This recycle will cause higher dust loadings which could result in potentially more erosive conditions than in the convective heat transfer region of a conventional boiler. Conversely, because of lower combustion temperatures, the AFBC dust is much less erosive. Tests in the pilot plant will determine actual erosion rates.

Recycle

The original design for the AFBC pilot plant incorporated a carbon burn-up bed in order to achieve acceptable combustion efficiencies and limestone utilization. Based on the results of recent research, the 20-MW AFBC pilot plant was designed to return elutriated fines containing unburned coal and limestone back to the main combustor without the use of a carbon burnup bed. Through the use of recycle, combustion efficiencies of about 99 percent are expected, and sulfur capture greater than 90 percent can be economically achieved.

The pilot plant was initially designed with a 752°F (400°C) recycle, with recycle rates of up to five times the coal-feed rate. Provisions have also been made for a 1550°F (843°C) recycle to be added later. It is predicted that with the designed recycle rate, 90-percent sulfur capture can be achieved with a calcium-to-sulfur ratio of 2:1 or less.

TVA's 20-MW AFBC PILOT PLANT - TEST PROGRAM

An important part of the pilot plant project, to which much attention is also being given, is the test program. There are six major tasks which describe the activities required to accomplish the test program objectives. These are:

Task I, Test Engineer Training: Activities were conducted at various facilities to indoctrinate and train the test engineers in AFBC theory and practice. Computer systems, boiler controls, sampling, and data reduction techniques have been emphasized.

Task II, Procedure Development: A set of standard test and operating procedures is being developed by the personnel who will be operating the unit and conducting the test program.

Task III, Computer Software Development: Various data reduction routines are being developed to efficiently and effectively handle the large amounts of data produced during the test program.

Task IV, Cold Mode Testing and Calibration: A preoperational, shakedown phase will condition the pilot plant for light-off and steam production. This will include the contractor operability tests and generation of initial baseline performance data.

Task V, Hot Mode Testing Campaigns: This is the major thrust of the test program. The basic design as well as modifications will be tested and evaluated to develop AFBC technology and enhance larger-scale demonstration designs and, thus, commercialization of the technology.

Task VI, Data Reduction, Analysis, and Results Presentation: Data packages for each test and initial data analysis will be prepared at the test site. The major data analysis and reporting will be accomplished by the project staff located in TVA's Chattanooga offices.

A formal test plan has been developed by EPRI and TVA to serve as the control document for the test program. The test plan provides an overall research and development strategy and establishes priorities for testing. Flexibility is built into the test plan to allow for a variety of testing decisions as well as changes in developmental priorities.

The test program is scheduled to extend into 1986. The test plan establishes three phases of activities:

- Late 1981 to mid 1982: Startup and acceptance testing
- Mid 1982 to mid 1984: Phase I campaign testing
- Mid 1984 to mid 1986: Phase II campaign testing

Startup and acceptance testing is well underway. The activities include component and system acceptance, including cleaning, shakedown, and run-in; collection of preliminary data and information regarding component and system performance, operating characteristics, and baseline measurements; calibration and checkout of instrumentation including process monitoring, controls, and performance analyses; and a series of preoperational tests on the material handling, preparation and feed systems, the air and flue gas systems, and the boiler systems.

Upon verification that the facility is acceptable for formal testing, a two-phase program of test campaigns is planned:

Phase I:

Campaigns for Phase I testing have been identified and scheduled as shown in Figure 8.

Campaign I: Shakedown testing and baseline characterization - Reliable data is essential to the key decisions to be made in later campaigns. The shakedown and calibration tests will transform the pilot plant from a mere operating facility into a credible development tool. Confidence will be obtained in test procedures and operations through repetitive experimental verification so technology investigations can proceed. Test unit reliability will be demonstrated and baseline performance measured as a basis for later comparison.

Campaign II: Feeding and turndown method screening and selection - Feed-system design could have a major effect on the demonstration plant configuration. The various systems will be tested, compared, and evaluated, and the results will be quantified. The selected system will be incorporated into demonstration plant design. Later testing of one of the two feeding methods will determine its compatibility with a turndown technique.

Campaign III: Steady-state turndown and open-loop transient characterization - Turndown methodology will be established and transients characterized as a basis for control system design. Data will be obtained for dynamic model validation in developing an analytical approach to control system design for AFBC.

Campaign IV: Advanced control system implementation and testing - A multivariable control philosophy and design basis for the pilot plant will be implemented and demonstrated as a basis for commercial scaleup.

Phase II:

Campaigns for Phase II will be based on results obtained from Phase I and developmental priorities of the utility industry. Potential Phase II activities may include tests of alternate fuels and sorbents, further improvements or modifications to the control system, streamlining fluid bed combustor auxiliary systems, alternate superficial velocities, and possibly high temperature fines and baghouse recycle.

150- to 200-MW AFBC DEMONSTRATION UNIT

During the past few years, TVA, as well as other utilities, has been faced with changing load forecasts, funding constraints, as well as environmental and siting requirements. In light of these factors and others, three alternate options were investigated by TVA for the demonstration of AFBC technology for utility use. These are:

- Additional capacity through a new stand-alone 200-MW AFBC power plant.
- Replacement of an existing PC boiler with a 150- to 200-MW AFBC add-on* unit.
- Replacement capacity through AFBC retrofit** of an existing PC boiler (150- to 200-MW).

Considerable work has already been performed for the stand-alone 200-MW AFBC option. Final conceptual designs for an AFBC stand-alone demonstration plant and auxiliary equipment were completed by three boiler manufacturers in January 1981. TVA developed the architectural layout and the balance-of-plant (BOP) equipment layout for each contractor's design. A detailed boiler specification was prepared along with a schedule and cost estimate for a stand-alone 200-MW AFBC demonstration plant. A draft Environmental Impact Statement (EIS) was also completed.

Our present schedule (Figure 9) allows a reasonable amount of time to evaluate the pilot plant test results prior to freezing designs and committing to a demonstration option. On this timetable, completion of the demonstration unit is projected for 1989. A decision on the first commercial units based on this technology would then be possible in the 1990-1995 timeframe with a unit coming online in the late 1990s.

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*Add-On: An AFBC boiler built along-side an existing conventional boiler in a separate building for the purpose of replacing the existing boiler and its steam supply to the existing turbine.

**Retrofit: An AFBC boiler built in the space occupied by an existing conventional boiler for the purpose of replacing the existing boiler.

Persuing a replacement option has broad National interest. A recent Ebasco Services, Inc., study, based on Federal Energy Regulatory Commission EEI data, indicates that by 1995 there will be 857 fossil plants nationwide in the range of 4- to 217-MW which will be 40 years old or more. The combined capacity of these plants is approximately 53,000 MW. TVA alone has 51 units totaling 8773 MW which will be 40 years old, or older, by the mid to late 1990s. Many of these older units will be needed to provide "intermediate" and "peaking power" but are not designed to efficiently perform in this manner. Faced with these conditions, a promising option might be to replace an old, inefficient boiler with an AFBC boiler by retrofitting or adding a unit adjacent to the existing boiler. TVA in conjunction with S&W and the Riley Stoker Corporation performed a prefeasibility retrofit study, and it was concluded that there were no major problems which would prevent removing an existing PC boiler and replacing it with an AFBC boiler.

Having completed our 200-MW stand-alone demonstration plant design and looking at the economics of demonstrating AFBC as a reliable utility option for burning coal, our current activities are directed at studying the replacement options of a retrofit unit and an add-on unit. Through fiscal year 1982, we will be involved in the conceptual engineering activities (Phase I) of selecting an existing TVA unit for replacement, developing site specific conceptual boiler designs for retrofit and add-on options, developing a boiler specification, determining the BOP modifications required, estimating the cost and schedule for the detailed design and construction phase (Phase III), and developing a funding consortium. In fiscal year 1983, we will proceed with the Phase II activities which include preparing the environmental assessment or EIS, developing a detailed boiler specification, developing the final conceptual designs for the BOP modifications, and developing a ±10-percent cost estimate for Phase III. These activities will support our request to obtain TVA Board approval to place the Phase III detail design and construction contract by September 1984. Projected completion of the replacement unit is May 1989.

ADDITIONAL TECHNICAL SUPPORT ACTIVITIES AT TVA

Feed System

One of the potential problems with AFBC, as well as with other coal burning technologies, is in the development of a reliable coal/limestone feed system. In order to address this problem prior to starting the 20-MW AFBC pilot plant, a project involving the testing of a full-size Fuller-Kinyon pump feed and splitter system was initiated. A test facility (Figure 10) constructed at TVA's Watts Bar Steam Plant simulated operating conditions by utilizing coal from the plant's coal pile and presized limestone procured from outside. A 12-month testing program was recently completed. The Fuller-Kinyon pump, from the cement industry, appears to be uniquely well suited for feeding an AFBC boiler. This facility will help to ensure against pilot plant operational delays and will increase the probability of successful performance for demonstration and commercially sized AFBC.

Recycle

The EPRI/B&W 6 ft x 6 ft AFBC unit at Alliance, Ohio, has provided evidence that adequate carbon utilization and a significant decrease in limestone utilization could be obtainable simply by recirculating a portion of the fly ash to the combustor rather than using a second combustor. Tests of this approach with high recycle rates have also been undertaken at Oak Ridge National Laboratory (ORNL) and at General Atomic (GA). They have found that a calcium-to-sulfur ratio of 2:1 is obtainable at reasonable recycle ratios. Follow-on work at GA is designed to obtain more exact trends of carbon and calcium utilizations as a function of recycle ratio.

Modeling to Improve Scaleup and Automatic Control

A predictive steady-state model for the 20-MW AFBC pilot plant has been developed. To verify the model, a moderate amount of additional experimental work is being undertaken to provide more data on mass transfer between bubbles and the emulsion phase and on devolatization rates with small coal particles. In addition, to improve process automation, a transient model has been developed. The objective of the model is to combine theory and testing for process improvement and extrapolation to larger-scale plants on a sound basis.

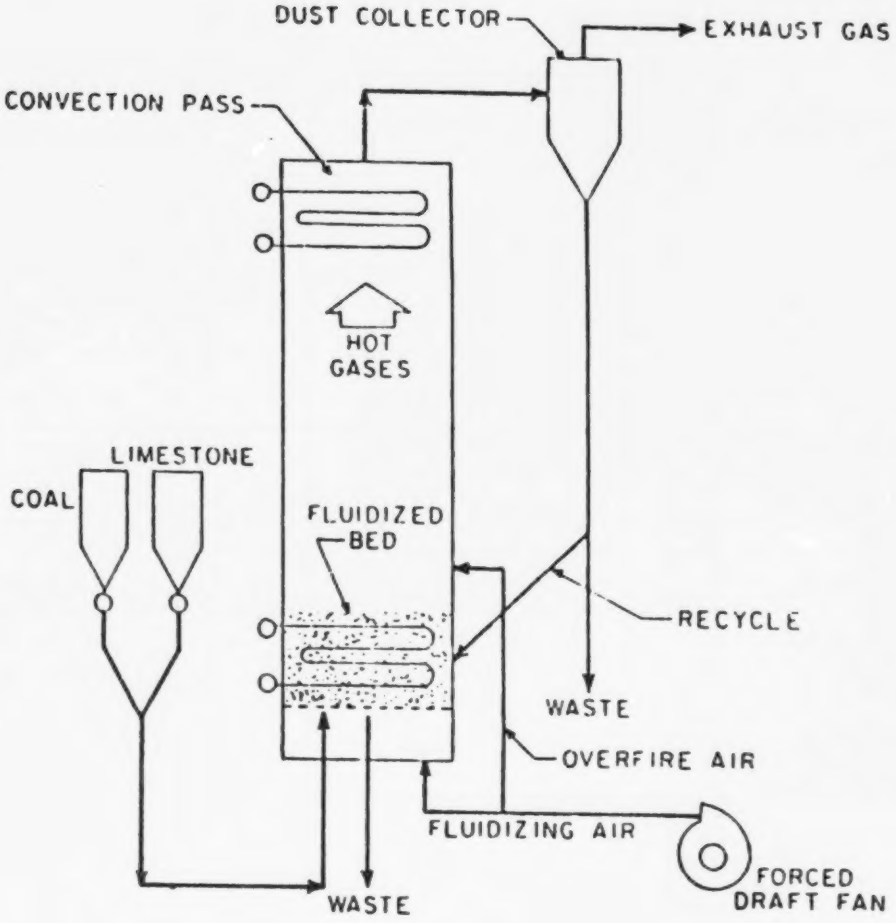
Boiler Materials of Construction

Earlier concerns over sulfidation of nickel in T304 stainless-steel superheater tubes, with potential in-bed reducing atmospheres, do not appear to be a problem. The absence of attack in hot tests at low oxygen levels in studies at FluiDyne and ORNL indicate a satisfactory performance under these conditions. It is now believed that standard boiler materials may be used with due regard to maintaining an oxygen excess through correct design and process control. The 20-MW AFBC pilot plant should provide the required confirmation that standard practices are adequate.

Conclusions

Based on recent technology improvements, the economics and attractiveness of AFBC has been significantly enhanced. Some of the more significant improvements include boiler designs, which provide adequate residence time for reactions in the bed and freeboard area; the use of increased recycle of elutriated fines; and the introduction of secondary air above the bed for 2-stage combustion. With these changes, the calcium-to-sulfur stoichometry required for 90-percent sulfur removal has been cut in half. Carbon utilization has been increased to the 99-percent level required for utility applications, and oxides of nitrogen should be in the range of

.3 lb/MBtu (.129 kb/GJ). The 20-MW AFBC pilot plant, which is undergoing acceptance testing, is expected to confirm the performance capabilities which have been achieved in smaller units and provide the design information needed to confidently scale-up this technology for use in utility-size AFBC boilers.


DUST COLLECTOR
EXHAUST GAS
CONVECTION PASS
HOT GASES
LIMESTONE
COAL
FLUIDIZED BED
RECYCLE
WASTE
OVERFIRE AIR
FLUIDIZING AIR
FORCED DRAFT FAN
WASTE

SIMPLE AFBC PROCESS SCHEMATIC

FIGURE 1.

FLUIDIZED COMBUSTION PERFORMANCE TRENDS

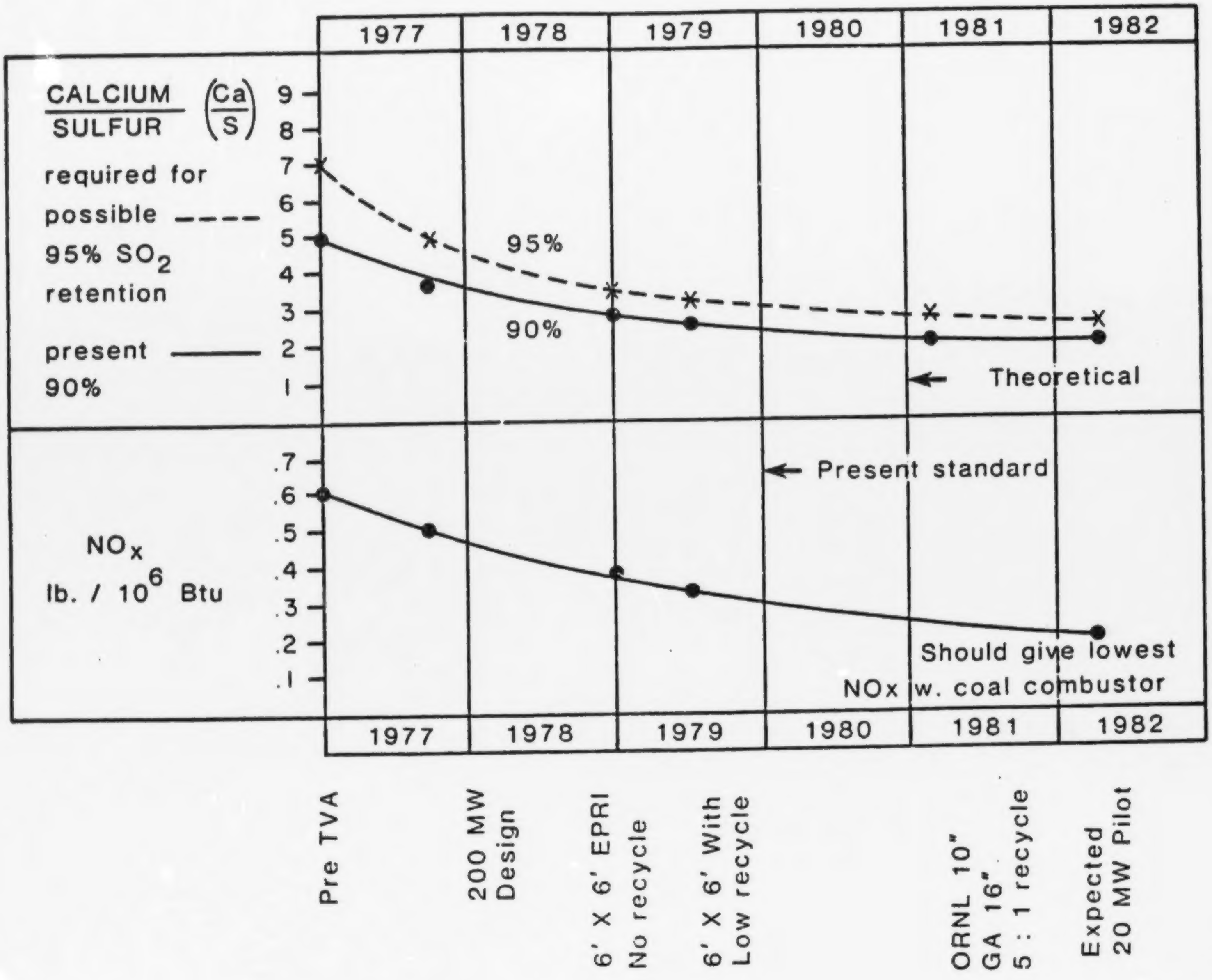


FIGURE 2.

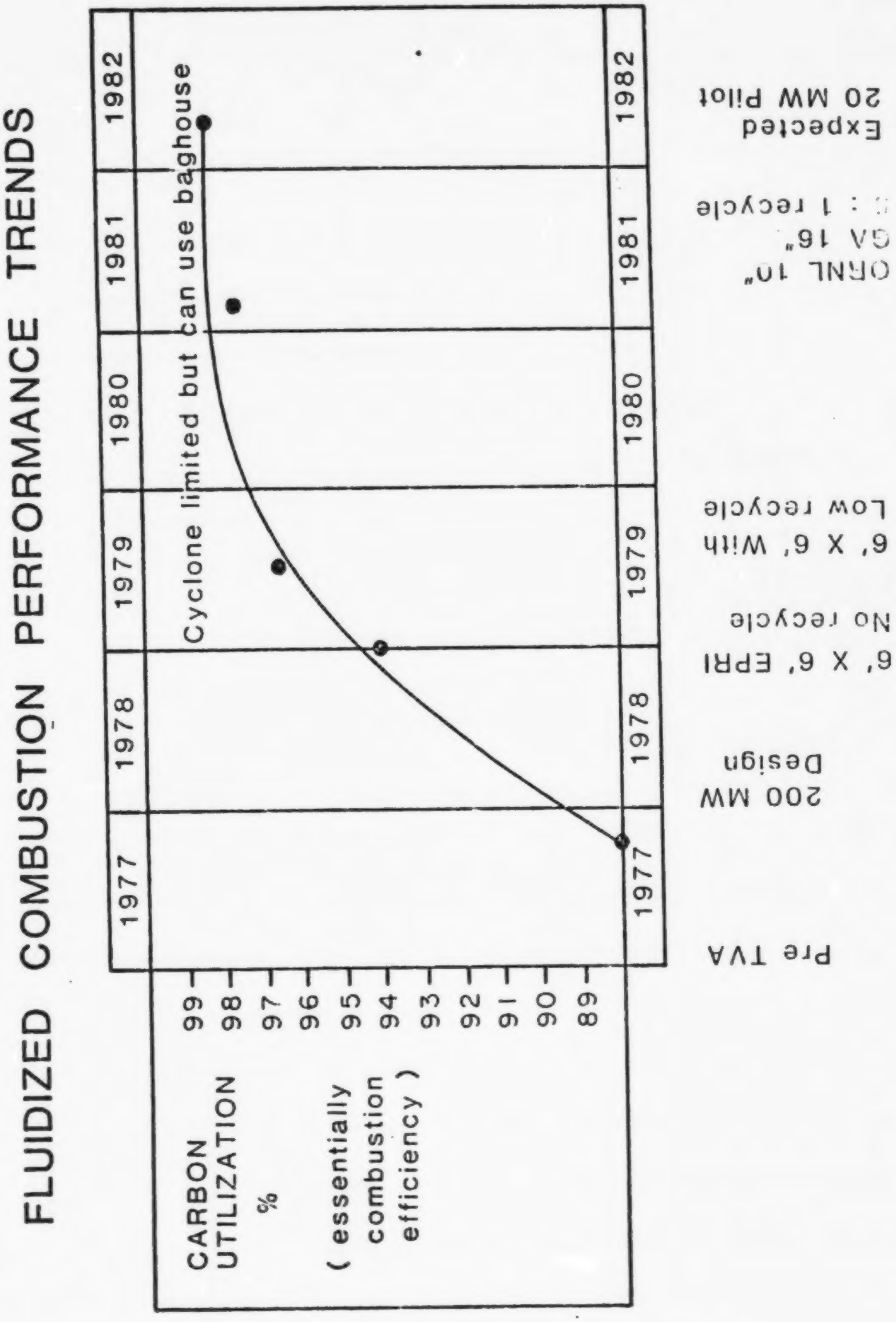

FLUIDIZED COMBUSTION PERFORMANCE TRENDS
CARBON UTILIZATION %
(essentially combustion efficiency)
99
98
97
96
95
94
93
92
91
90
89
1977
1978
1979
1980
1981
1982
Cyclone limited but can use baghouse
Pre TVA
200 MW Design
6' X 6' EPRI No recycle
6' X 6' With Low recycle
ORNL 10"
GA 16"
: 1 recycle
Expected 20 MW Pilot

FIGURE 3.

AFBC PILOT PLANT SCHEDULE

FACILITY PHASE

CALENDAR YEARS

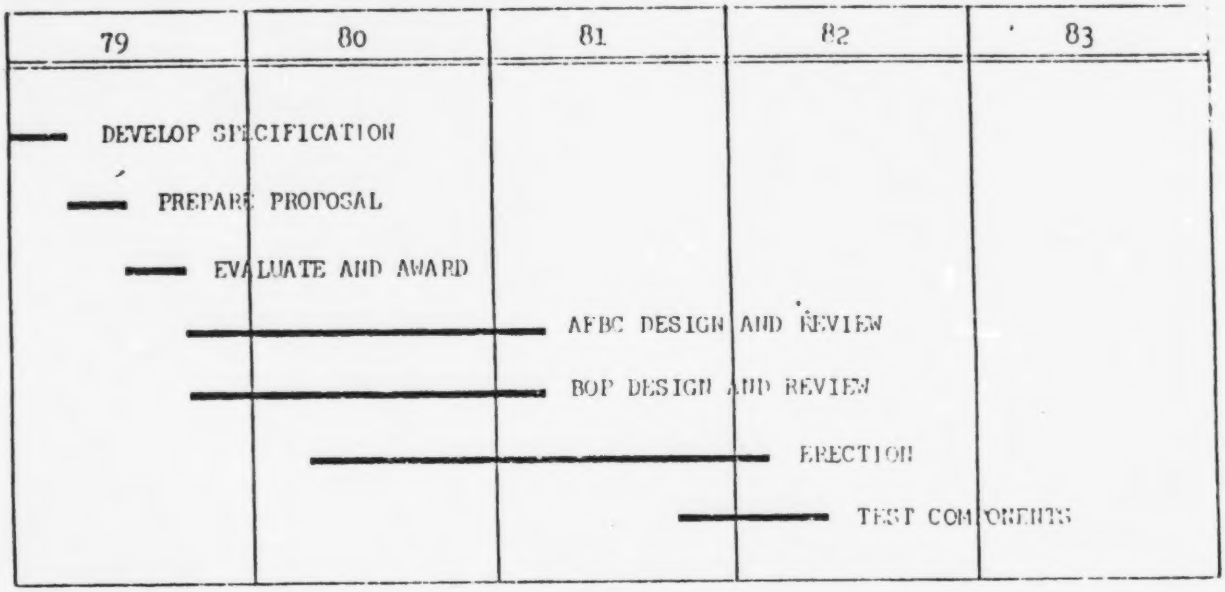


FIGURE 4.

AFBC PILOT PLANT SCHEDULE

TEST PROGRAM PHASE

CALENDAR YEARS

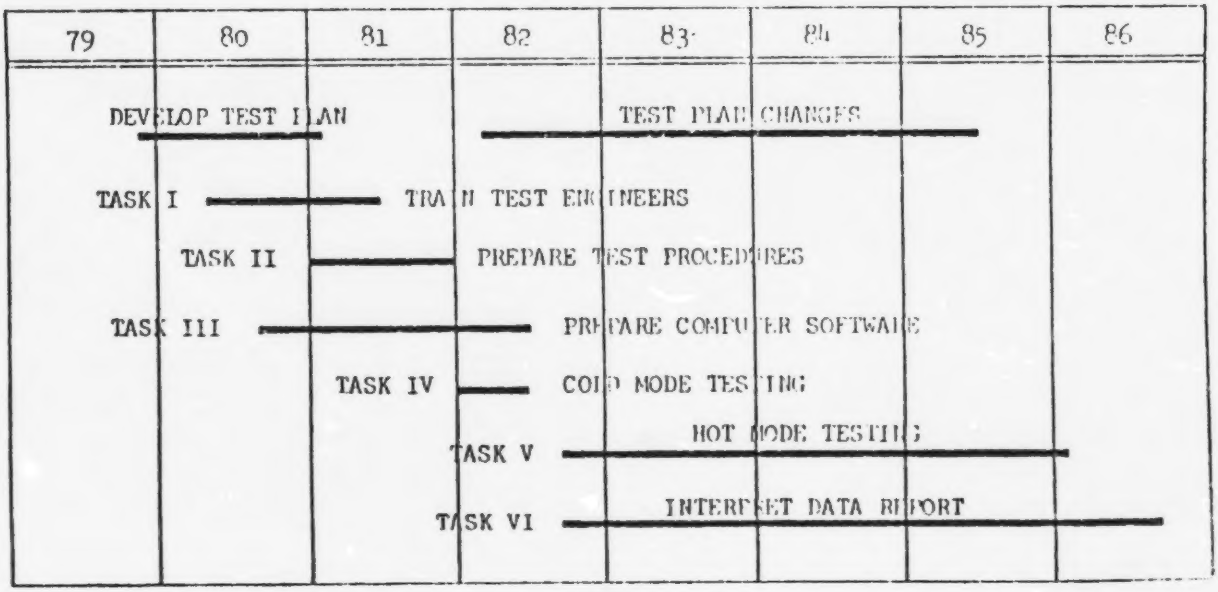
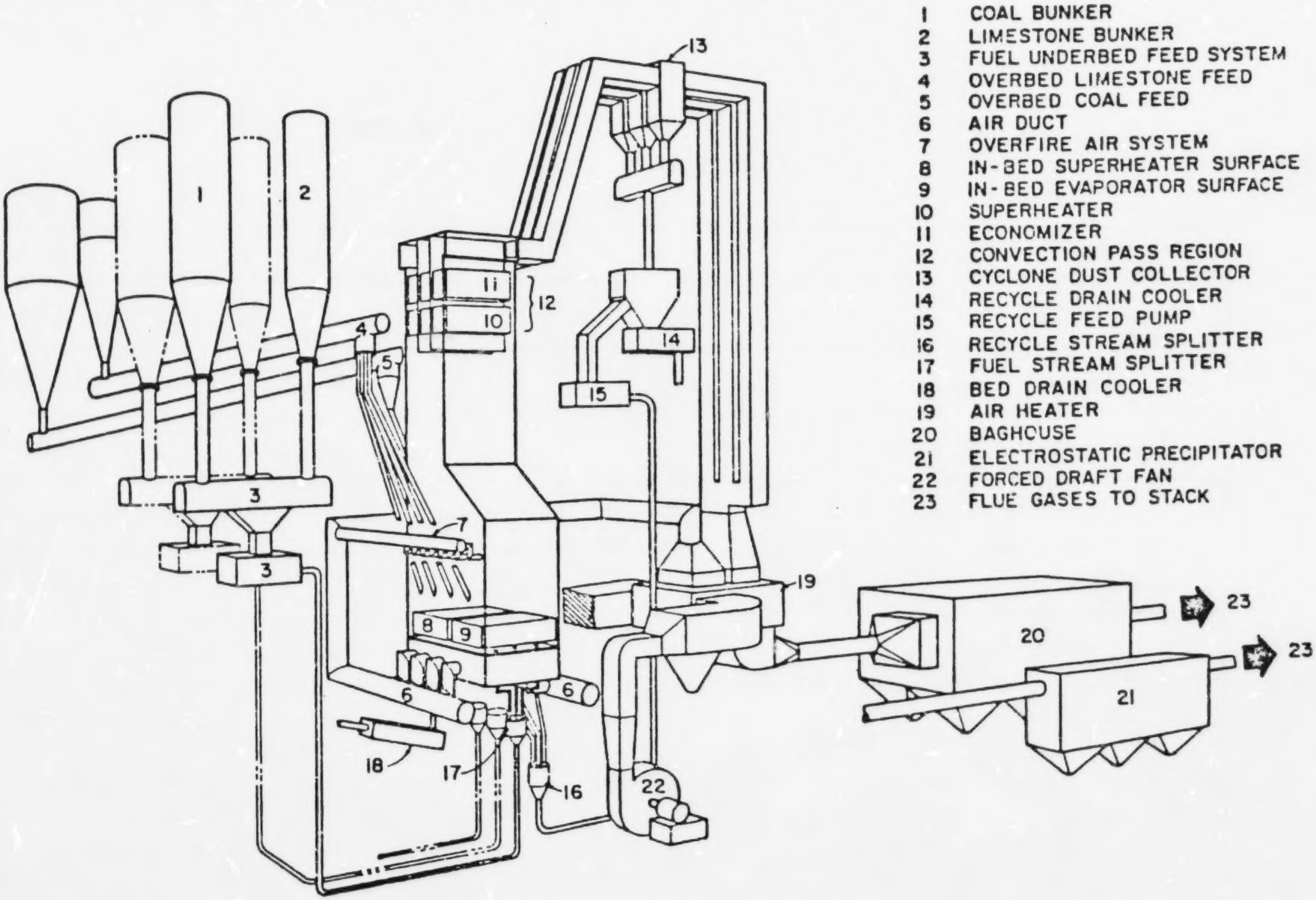


FIGURE 5.


1 COAL BUNKER
2 LIMESTONE BUNKER
3 FUEL UNDERBED FEED SYSTEM
4 OVERBED LIMESTONE FEED
5 OVERBED COAL FEED
6 AIR DUCT
7 OVERFIRE AIR SYSTEM
8 IN-BED SUPERHEATER SURFACE
9 IN-BED EVAPORATOR SURFACE
10 SUPERHEATER
11 ECONOMIZER
12 CONVECTION PASS REGION
13 CYCLONE DUST COLLECTOR
14 RECYCLE DRAIN COOLER
15 RECYCLE FEED PUMP
16 RECYCLE STREAM SPLITTER
17 FUEL STREAM SPLITTER
18 BED DRAIN COOLER
19 AIR HEATER
20 BAGHOUSE
21 ELECTROSTATIC PRECIPITATOR
22 FORCED DRAFT FAN
23 FLUE GASES TO STACK
1
2
3
3
4
5
7
8
9
10
11
12
13
14
15
6
6
18
17
16
22
19
20
21
23
23

TENNESSEE VALLEY AUTHORITY
20 MW AFBC PILOT PLANT

FIGURE 6.

20-MW AFBC PILOT PLANT OPERATING PARAMETERS

	DESIGN	*FLEXIBILITY*
BED DEPTH	1.2 m	1.2 - 1.8 m
FLUIDIZING VELOCITY	2.4 m/sec	1.2 - 3.7 m/sec
COAL FEED RATE	5.3 t/hr	up to 10.3 t/hr
LIMESTONE FEED RATE	2.2 t/hr	up to 12.2 t/hr
RECYCLE RATE/COAL RATE	1.8	5 max
CALCIUM/SULFUR (MOLAR)	2.8*	1.9 - 6.0
MAIN STEAM		
FLOW RATE	50,461 kg/hr	up to 76,082 kg/hr
TEMPERATURE	538°C	538° C
PRESSURE	16,546 kPa	16,546 kPa

*2.0 PREDICTED FOR RECYCLE RATIO = 5

FIGURE 7.

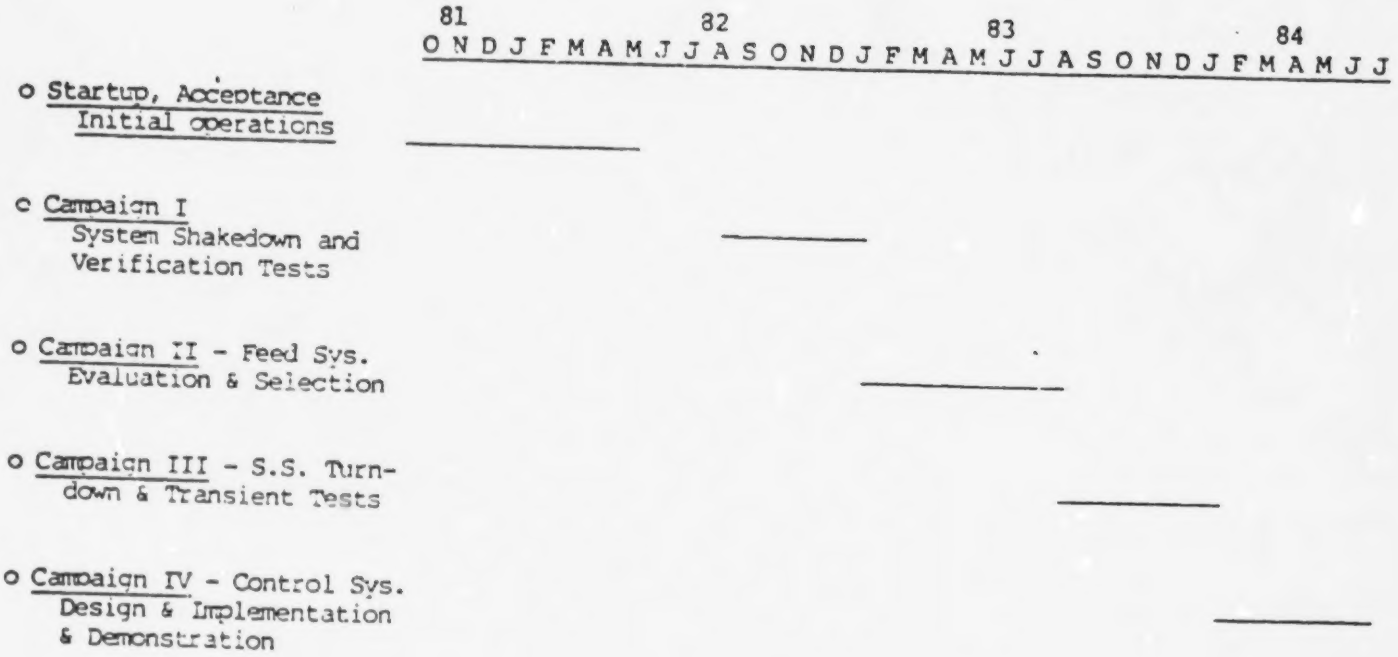


Figure 8: Test Plan Schedule for Phase I

TENNESSEE VALLEY AUTHORITY
ATMOSPHERIC FLUIDIZED BED COMBUSTION
PILOT PLANT AND DEMONSTRATION UNIT SCHEDULE

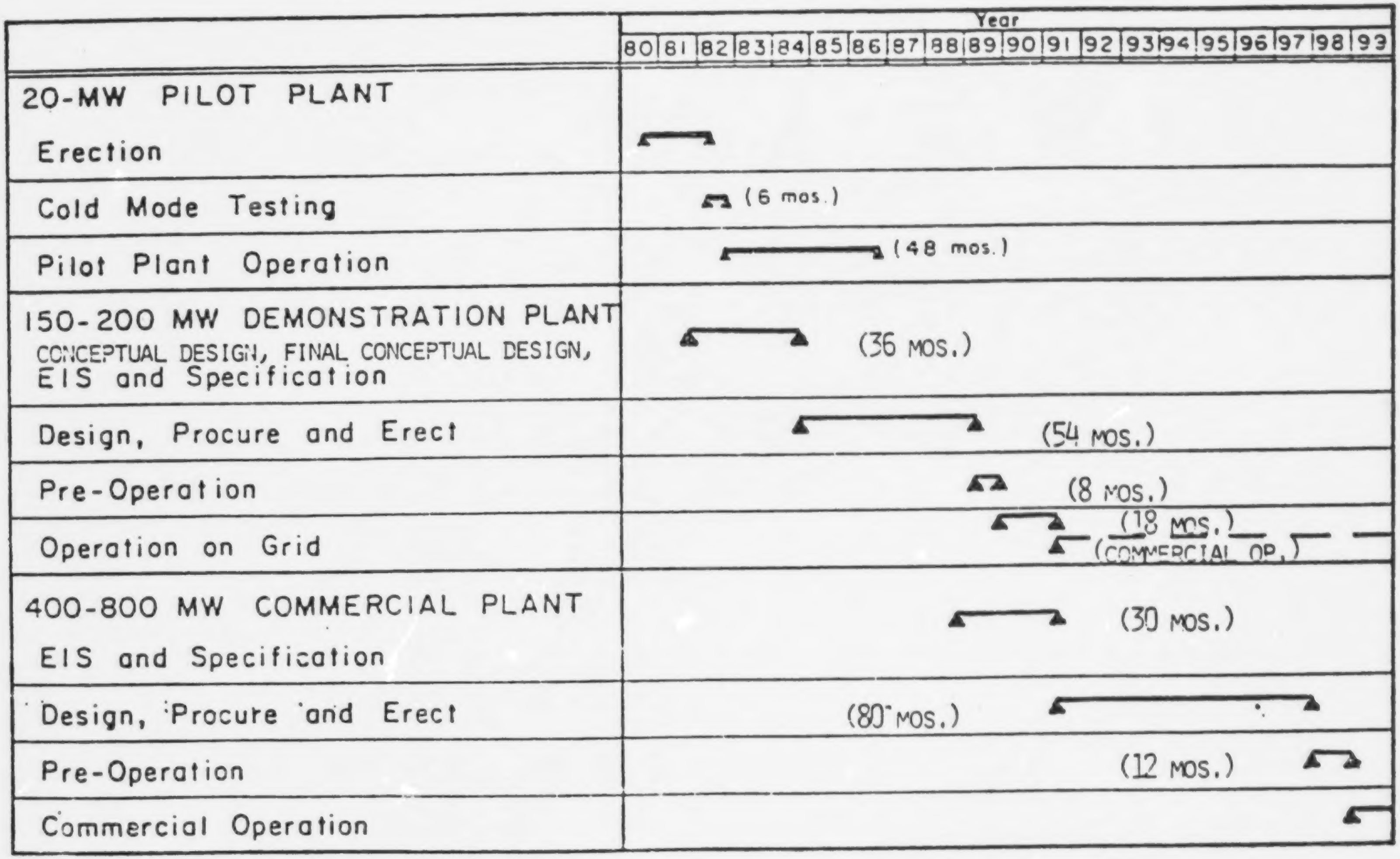
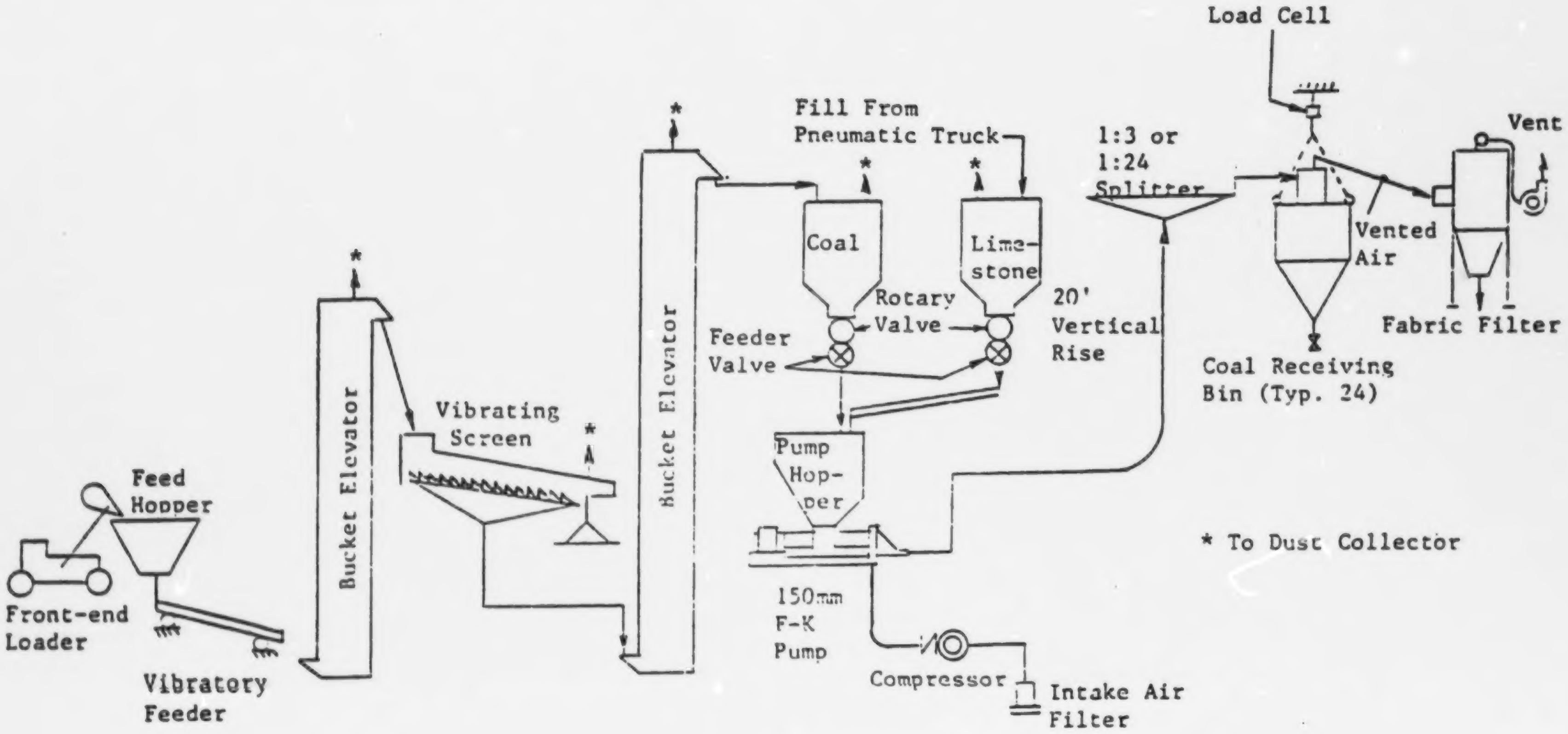


FIGURE 9


Load Cell
Fill From
Pneumatic Truck
Vent
1:3 or
1:24
Splitter
Coal
Lime-
stone
Vented
Air
Rotary
Valve
20'
Vertical
Rise
Fabric Filter
Feeder
Valve
Coal Receiving
Bin (Typ. 24)
Vibrating
Screen
Bucket Elevator
Bucket Elevator
Pump
Hop-
per
Feed
Hopper
* To Dust Collector
Front-end
Loader
150mm
F-K
Pump
Vibratory
Feeder
Compressor
Intake Air
Filter
*

SCHEMATIC - Watts Bar Test Facility

Figure 10.

Technical Barriers to AFBC Utilization

John Stringer and Shelton Ehrlich

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California

Introduction

In one sense, there are no technical limitations in the development of AFBC. To some extent, it depends upon what is meant by commercial development, and what sort of AFBC. There are many small AFBC's operating now, producing hot water or low quality steam; and for this sort of application there are few real problems. However, for more advanced systems, the problems increase; and the purpose of this paper is to discuss some of these.

The problems are related to the difference between conventional pulverized coal boilers and pulverized coal systems. These are:

1. Coal feeding
2. Limestone feeding
3. Ash removal
4. Calcium utilization/sulfur retention
5. NO_x control
6. Solid waste disposal
7. Combustion efficiency
8. Load following capability
9. Materials of construction: corrosion and erosion

In these terms, it is necessary to review the design of different AFBC systems.

The benefits of fluidized bed combustion are:

a. The ability to burn a very wide variety of fuels, including those with very low heating values, high ash content, and a wide variety of types.

b. The ability to remove sulfur within the bed by including an acceptor, typically limestone, which first calcines in the bed to produce calcium oxide and then reacts with the sulfur to form calcium sulfate.

c. The production of very low NO_x emissions; this is associated with the low combustion temperature.

d. The very high heat transfer within the bed, resulting in a lower total surface area for the heat exchanger within the bed; if this is the finishing superheater or reheater, the usage of the more expensive tubing materials is minimized. Furthermore, the overall size of the unit will be smaller than a conventional boiler.

A further possible advantage is the production of a solid waste product which is environmentally acceptable. Of course, in order to prevent the fine dry product blowing about, and in order to restrict the dangerous character of the unslaked residue, it will be necessary to "damp down" the ash with water. Nevertheless, the water usage will be less, and it will not be necessary to use settling ponds.

Solids Handling

The majority of the larger beds use underbed feeding of the coal and limestone. The principal reason for this is that it is felt to promote better mixing of the reactants, resulting in improved combustion efficiency and sulfur capture. It is believed that for a typical AFBC, one coal feed port is required for each ten square feet of bed area, although this does not appear to have been established with any certainty, and recently designs have tended to increase that area. As a rough rule of thumb, this is equivalent to one port per MW(e); so a 1000 MW(e) boiler would require 1000 ports and associated coal feed lines. In the majority of cases the coal is injected into the bed pneumatically. The jet velocity has to be sufficient to encourage good mixing, but not so great as to penetrate the bed completely, or to produce erosion of surfaces within the bed. As part of the turn-down procedures, coal feed may be interrupted at some of the coal feed ports. In this case, it is desirable that there should be no coal remaining in the portion of the feed line close to the combustor since the line may block. However, it is also desirable to prevent the backflow of bed material into the line. At the 6-ft x 6-ft AFBC at Babcock and Wilcox, Alliance, Ohio, a valve device is being tested: this consists of a disc in a cage. The valve is required to lift when the coal is flowing in, but to seat on the pipe end when flow is halted. During operation, the coal-air jet is directed against the bottom of the disc, and the disc is rapidly cooled from bed temperature. The material has thus to exhibit good erosion and thermal shock resistance.

In large units the coal feed lines typically have vertical sections up to the distributor plate, and long horizontal sections to the flow splitter. The transition is clearly a location where erosion of the lines by the coal stream is likely to be a problem.

The uniform splitting of the coal stream into separate streams for each coal feed port is a considerable problem. Present splitting and underbed pneumatic feeding systems require the coal to be dry, typically with less than 5% moisture. This is calls for additional development, for the moisture restriction limits the flexibility of the AFBC.

The alternative is overbed feeding. Relatively large coal can be burnt in this way, although if it is too large lumps of coal or ash may sink to the bottom of the bed and eventually result in local defluidization. However, it is difficult to prevent the fines from blowing off before they have the chance to be mixed in the bed. This is a considerable disadvantage, since modern run-of-mine coal may contain of the order of 30% fines. Overbed feeding is accomplished with spreader stokers, which throw the coal in through a wall port; but achieving uniform feeding with a large unit would be difficult, and may require development of improved stokers. In addition to affecting the combustion efficiency, it is believed that there is a risk that the sulfur capture efficiency would be reduced, since some devolatilization and burning would take place before the coal had been mixed into the reactive bed. However, the desulfurization reactions can take place with the elutriated calcinated limestone fines in the freeboard, and some preliminary evidence suggests that the loss in capture efficiency may not be as great as was once feared. This point will be studied more carefully on the TVA 20 Mw(e) demonstration unit, which has facilities for both underbed and overbed feeding. Overbed feeding has the additional advantage that relatively wet coal can be handled.

One possibility is to feed the fine coal under the bed and the coarse coal overbed. It may appear that this introduces additional complications--the coal will have to be dried so that the fines can be separated, the dried coal will have to be classified, and two feed systems will have to be used. However, the benefits are that the crushing and top sizing steps are essentially eliminated, and the loading of, and hence the problems with the underbed system would be greatly reduced. Furthermore, the operability of the system would be less sensitive to that of the underbed feed system. A further possibility is to use a high density coal water slurry, which could be handled much like a liquid fuel. By comparison, the problems of preparing and feeding the limestone are minimal.

The other major solids problem is ash handling. There are several ash handling systems. First, there is a bed removal system. This is required on a periodic basis for draining the bed at the end of a campaign, but it is also required on a more frequent basis for bed level control. The bed level is controlled in two ways: first, for normal steady-state operation the bed level must be approximately constant. Calcium sulfate and ash are generated in the bed, and some is removed by elutriation. If the amount removed in this way is less than the amount charged, the bed level will rise, and material will have to be drained from time to time. The bed drains are usually pipes in the distributor plate, the diameter of which is determined by the length of time required to dump the bed in an emergency, at least for a non-circulating bed. Flow is controlled by valves, which are situated far enough away that when the drain is not operating they are at a low temperature. The pipe between the valve and the bed is filled with an unfluidized column of bed material. If a bubble cap distributor is used, the top of the column will not be particularly hot, and the temperature will fall to the valve. There should thus be few corrosion problems in the line itself, although the environment will be potentially aggressive. It will be very important to ensure that the whole column is above the appropriate dewpoint, whatever that is. It has commonly been assumed that because of the presence of a large excess of unreacted CaO and unhydrated $CaSO_4$, the water partial pressure would be so low that dewpoint problems could be ignored. Some recent results suggest that this may not always be true, and studies of this factor will have to be carried out.

During operation, the temperature of the line and the valve will rise very rapidly. Thermomechanical fatigue may well be an issue, particularly because of the wide variation in section thicknesses in the pipe and the valve components. Because of the relatively short time at temperature corrosion, of itself, should not be a problem and erosion, while it will have to be considered, also should be a minor problem in a properly designed system. However, the interaction of corrosion and erosion with the thermomechanical fatigue situation may well be important, as for example in the crazing of cylinder heads in IC engines.

Alternative bed removal systems have been designed involving (for example) S-bends which are normally defluidized and therefore blocked; they can be fluidized by the injection of air at the bottom of the bend, allowing the flows of material out. Concepts like this, involving no moving mechanical parts, are clearly attractive.

The remaining ash handling systems are concerned with the material entrained in the gas stream. Eventually, the combustion gas will be cleaned with a baghouse before venting to the stack. The baghouse should not present problems very different from those in conventional coal-fired boilers or in cement plants, limestone kilns or a variety of other plants. However, between the combustor and the baghouse there will have to be at least one additional separation stage. This will certainly involve an inertial separator such as a cyclone. The reason for this is not merely that the elutriated solids loading is far too high to be passed to the baghouse, but also that the elutriated dust contains a significant quantity of unreacted carbon. Attainment of reasonable combustion efficiencies requires that this is captured and burnt. Fortunately, virtually all of the unreacted carbon is captured in the first cyclone.

To a first approximation, the efficiency of an inertial separator depends directly on the gas velocity and inversely on the radius of curvature of the gas path. However, the higher the gas velocity the greater the pressure drop (and hence the energy loss), and also the greater the risk of erosion damage. Consequently, efficient separation implies a limit on the diameter of the cyclone, and thus handling a large volume of gas from a big AFBC will require a number of cyclones in parallel, or an arrangement resembling a large multiclone. Designing these to operate efficiently, detecting individual cyclone malfunctions, and remedying these on-line present a number of problems. The accumulation of material within the cyclone assembly is potentially very dangerous, since it is fairly hot (probably of the order of 350-400°C, depending on how the system is designed), and on start-up contains a significant amount of carbon: a fire is a real possibility and would be very damaging.

The catch from the first cyclone assembly must be returned to combust the unreacted carbon. Early designs such as the Rivesville AFBC used separate carbon burn-up cells without heat exchangers to achieve this, but now it is anticipated that the catch will be reinjected into the main bed. Because the catch has, after all, been elutriated already, it would appear that it would have to be injected pneumatically at the bottom of the bed to achieve reasonable residence times. This can be a significant problem. Most existing units blow the recycle dust in through a single port, since mixing uniformity is less significant than for the coal; and to ensure reasonable penetration use relatively high injection velocities, up to 60 m/s. Such flows are potentially very erosive, both in the transport lines and within the bed itself. Furthermore, there is some evidence to suggest that long-range circulatory flow patterns in the bed can be generated by the recirculation jet.

Interestingly, recent studies at Alliance have suggested that underbed injection may not, after all, be necessary. Recycle fines injected just above the bed appeared to be largely entrained in the bed itself, at least so far as can be judged from the combustion efficiency, sulfur capture, and bed temperature.

In all solids removal, the problem of cooling the solids is of concern. The usual method is the use of a water-cooled screw: this component can be expected to suffer erosion and perhaps bearing wear. A second method is to use a secondary fluidized bed in which combustion does not take place: this approach is used in the Lurgi circulating bed.

Ash Disposal

Related to the problems of ash removal is the issue of how the ash is to be disposed of. The ash will consist of dry dust, that part of it from the baghouse being very fine. The principal constituents are anhydrous calcium sulfate, calcium oxide, and coal ash constituents, largely uncoverted clay minerals. The ash will have to be water sprayed to slake the unhydrated calcium salts and to prevent the fines from blowing around. At the same time, the formation of an uncontrolled solid gypsum mass will have to be avoided. The product itself is useful from an agricultural point of view: it has been shown not to be hazardous, and it will modify the consistency of clay soils. USDA tests have shown beneficial results with a range of crops.

Combustion Efficiency and Calcium Utilization

Combustion efficiency is largely related to the fines content of the coal. The keys to achieving good combustion efficiency are: (1) a long residence time; and (2) capture and reinjection of the elutriated carbon.

The carrot for the development of AFBC is its ability to use cheap fuel which is difficult to handle in conventional systems. Lignites will tend to give high elutriation rates. High ash coals and washery wastes present no intrinsic problem (but see later). Low reactivity fuels such as anthracite or graphite present problems: because of the slow combustion, the carbon content of the bed will be higher. For a bituminous coal the bed will typically be 0.1-0.5% carbon; for the low reactivity fuels it may be as much as ten times this. As a result, the "graphitic fuel" combustor is much more sluggish in its response to load changes.

Removal of sulfur to the levels required by legislation requires a calcium-to-sulfur ratio of around 3:1. This in itself is no great problem; but with a high sulfur coal, control of the bed level will require continuous bed draining. This will also remove some uncombusted carbon and unreacted limestone, thus reducing the effectiveness of the sorbent still further. It may be necessary to develop acceptable ways of treating this drained material. Furthermore, the selling point of flexibility of the technology requires that a wide range of limestones should be acceptable: reactivities vary quite significantly.

From these points of view, increasing the calcium utilization is important. The limit appears to be that the pores generated during calcination of the limestone are rapidly blocked as a result of the sulfation, so that the lime on the inner part of a particle of acceptor is inaccessible to the sulfur-bearing gases. It has been shown that the addition of chlorides can improve calcium utilization, apparently by modifying the pore structure generated during calcination. Sodium chloride is very effective, but is probably unacceptable because of its known deleterious effect on high temperature corrosion. Calcium chloride also seems to be effective, and has little effect on high temperature corrosion. However, the effect on cold-end corrosion has yet to be determined.

Recently, an interesting method was suggested by Johnson et al. at Argonne to improve calcium utilization. The method depends on selective hydration of the spent sorbent: the effect is to crack the outer shell of sulfated material, allowing gas access to the unreacted lime core. The reactivated sorbent is returned to the bed.

The regeneration of the sorbent has also been proposed, either via the reduction of the sulfate to sulfide, followed by reaction with steam and CO_2 to produce calcium carbonate and H_2S, or by direct reduction to calcium oxide and SO_2. The economics of these processes will be questionable until sulfur prices are somewhat higher than they are today.

Load-Following Capability

In a conventional furnace, the output can be varied over a wide range simply by turning down the fuel supply. Bypasses can then balance the duties of the different heat exchangers. Achieving the same flexibility in a fluidized bed is rather difficult: the air flow must be controlled within fairly narrow limits to keep the bed in the designed state of fluidization, and the bed temperature must always be high enough to allow coal to burn; furthermore, the requirement to maintain adequate sulfur removal places upper and lower limits on the bed temperature. The presence of the in-bed heat exchanger with its associated high heat removal rate further restricts the turn-down capability.

One method involves lowering the bed level so that some of the heat exchanger is exposed, lowering the heat transfer coefficients for that section. As will appear later, this may result in materials durability problems because of erosion in the splash zone. A second method segments the bed, and turns down by slumping different sections: this method is currently being studied on a moderate-sized boiler in the U.K. A further possibility involves the design of nonuniform heat exchanger bundles, so that as the bed is turned down the heat exchanger characteristics also change: this implies fairly detailed knowledge of the heat release distribution in the bed as a function of load.

Measurement of bed depth is simple, but does involve instruments that are not normally required in a power station. Feed rates of both coal and limestone are difficult to measure with accuracy. It has also been suggested that on-line compositional analysis of the feed materials, ash and effluents are desirable for proper control, and that bed temperature measurement accuracy needs to be improved. Stabilized zirconia electrolytic oxygen sensors may well become a useful tool for control by measuring the combustion processes directly.

Use of high recirculation offers another control strategy provided of course that there is heat exchange in the recirculation loop.

NO_x Production

The low combustion temperature favors reduced generation of oxides of nitrogen. Nevertheless, it may be necessary to attain even lower emissions to satisfy environmental legislation. It has been demonstrated that this can be done by reducing the excess air introduced through the bed; additional air is injected immediately above the bed surface. There are obviously penalties associated with this. Because of the uncertainties in the coal feed rate and the fuel analysis, the bed may well operate for a time substoichiometrically, and this may have consequences for the materials of construction in the in-bed heat exchanger.

Materials of Construction

The issues of erosion and wear in the solids handling systems have been mentioned above. In the main, there are two principal issues for materials in AFBC systems which are different from those in conventional pc units. These are: in-bed corrosion and erosion; and erosion in the freeboard.

Erosion in the freeboard may be a problem because of the high solids loading, much greater (by perhaps an order of magnitude) than that in a pc boiler. On the other hand, some preliminary data suggest that the erosivity of the fbc dust is significantly less than that of a typical pc fly ash, which may compensate in part for the high loading. Early large AFBC units will probably be designed with gas pass nominal velocities similar to the conservative end of current pc practice, of the order of 15-20 m/s. No testing has been done to determine how the erosivity of the fbc dust varies with the feedstock composition and character. It has been shown above that there appears to be important practical benefit to be derived from recirculation of elutriated fines, and even from deliberately increasing the degree of solids circulation. This will not only increase the solids loading, but may also increase the fraction of larger particles in the gas stream. There are certain advantages in using higher fluidizing velocities, 2-4 m/s rather than 1-1.5 m/s. This is difficult to achieve without recirculation since the residence times are usually too low; but if recirculation is used the barrier to these higher velocities is removed. This would certainly increase the fraction of larger particles in the gas stream, and may increase the erosion rate of convection-bank tubes that cross the path of the flue gas.

A possible solution to this problem is to use only water-wall heat exchangers in the recirculation loop. Since the particle flow is substantially parallel to the metal surface, the erosion should be minimal. There will of course be areas where the flow path results in particle impingement: these will have to be armored, most probably with refractory layers, but perhaps with hard facings.

After the relatively clean gas exits the recirculation cyclone, transverse heat exchangers can be used. It has been suggested that the design of a system with a high degree of recirculation is complex and loses some of the benefits of simplicity of the normal AFBC: there do not appear to have been any detailed objective comparative design and cost studies.

A more significant materials issue is the in-bed heat exchanger. At elevated temperatures, metals within the bed corrode by a process involving sulfidation followed by oxidation. In the case of nickel-base alloys the corrosion quickly becomes catastrophic, with the formation of liquid nickel sulfides which are then capable of corroding other alloys in their immediate vicinity. Other high-nickel alloys such as Inconel 800 behave in a more variable manner, sometimes apearing to corrode relatively slowly, but at other times suffering rapid intergranular attack.

The mechanism of the corrosion involves the presence of local low oxygen activety ("reducing") regions. It appears that the dense emulsion phase in the bed usually has a low oxygen activity, typically 10^{-13} atm or even less: the bubble phase is relatively oxidizing. In the presence of calcium sulfate, relatively high sulfur activities, perhaps as high as 10^{-5} atm, can be generated.

Very severe corrosion has been observed in the vicinity of coal feed ports. This suggests that longer-lived reducing regions, as might be expected in beds with uneven coal feeding or too few coal feed ports, or more directly in beds using overbed air injection to control NO_x, might result in accelerated attack. Interestingly, a run deliberately conducted under substoichometric conditions at CRE showed that the minimum oxygen activity was not greatly affected; but the total time at these conditions was increased. The corrosion of most alloys did not increase greatly, but some of the more sensitive materials did exhibit very severe corrosion.

It has been shown that crevices can promote rapid corrosion of otherwise resistant materials, presumably again because of restricted access of oxygen.

For steam raising, the maximum metal temperature will be of the order of 650°C. At this temperature, the conventional stainless steels Type 304 and Type 347 have exhibited acceptably low corrosion rates, certainly better than IN617 or Incoloy 800. However, internal sulfidation is observed. While it appears still to be benign up to 2000 hours, forming only isolated globular sulfide particles, the possibility of accelerating "breakaway" attack at larger times cannot be ruled out. Longer-term testing must be undertaken to establish this point.

Low-alloy ferritic steels undergo acclerated oxidation in the bed. This does not usually appear to involve sulfidation, but the mechanism has not yet been established. Certain problems wih tube temperature measurement limit the confidence one can have in the numerical data, but Babcock & Wilcox believe that the maximum permissible metal temperaure for these alloys is certainly no higher than 510C, and may be lower. This increases the relative proportions of the finishing superheater and reheater that have to be made of the more expensive austenitic alloys.

In addition, current practice is to make the "dissimilar metal" weld between the ferritic and austenitic sections using a nickel-based weld metal. This is clearly a risky thing to do, although the low temperature of the junction may limit the attack. The alternative is Type 309 austenitic filler, but this too has given cause for concern in some tests. More work needs to be done on this point.

A significant problem is the support structure for the in-bed heat exchanger. Unless this is cooled, which is not impossible but probably unacceptable in terms of complexity and expense, the metal will have to exhibit reasonable durability at bed temperature. On the other hand, the section thickness can be large, and of course they are not pressure parts. The high chromium steels such as Type 310 have appeared to be acceptable for this duty, although the sigma-proneness of this steel is a little worrying: bed temperature is almost exactly at the nose of the C-curve for sigma formation. High chromium FeCrAl alloys have seemed good, and coating or cladding may be a way out if the simple alloys prove ineffective in the long run.

AFBC air heaters have been proposed as combustors for gas turbine systems. In this case, tublar heat exchangers with modest pressure differences will have to run close to the bed temperature. This is a very difficult problem. No alloy could be recommended with confidence for lifetimes in excess of 5 years or so on the basis of our present knowledge, although if coextruded tube with Fe-25Cr-4Al-1Y clad over Incoloy 800H could be made, it would probably be acceptable.

In addition to in-bed corrosion, in-bed erosion has been a significant problem in many AFBC's, although equally many other units have run for thousands of hours with no problems at all. Erosion usually affects the cooler tubes: jets within the bed from various sources, notably fines reinjection points, and long-range circulatory flows within the bed have been blamed for some of the erosion incidents. Relatively high-velocity particles are present in the splash zone, and there is some evidence for accelerated erosion of tubes immediately above the bed. At the moment, this aspect is imperfectly understood, and more work needs to be done.

Lastly, the issue of fatigue of the in-bed structure needs to be considered. There are considerable varying forces on objects within bubbling fluidized beds, and both fretting against the supports and fatigue must be considered. Fretting has been observed at Rivesville, but there has as yet been no documented instance of a fatigue failure of an in-bed component. This may, however, be due to the relatively small lengths of the tube in existing units and the relatively short total exposure times. More work needs to be done to determine the magnitude of the forces and to estimate fatigue lifetimes for large structures.

Conclusion

Nine technical barriers were listed that inhibit the utilization of AFBC in the more demanding applications (industrial and utility power generation). A number of solutions have been proposed and some are being tested in various pilot and commercial units operating around the world. The materials issues need relatively long tests for resolution and we expect such tests to occur.

DEVELOPMENT OF ATMOSPHERIC FLUIDIZED BED COMBUSTION (FBC) BOILER TECHNOLOGY FOR POWER GENERATION IN JAPAN

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Development of Atmospheric Fluidized Bed Combustion (FBC) Boiler Technology for Power Generation in Japan

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I. Introduction

1. Present and future of coal-fired power generation in Japan

(1) Outlook of Overall Energy Balance

The general trend of overall energy balance in Japan is disclosed by the Ministry of International Trade and Industry (MITI). The outlook is reviewed at the interval of a few years reflecting the change of situation occurring from time to time. In Table 1 is shown the latest outlook issued by the MITI in April, 1982.

TABLE 1. OUTLOOK OF OVERALL ENERGY IN JAPAN

(MITI 1982)

FISCAL YEAR / ITEM	1980		1990	
ENERGY CONSUMPTION (ENERGY SAVING RATIO)	429 ^{M}kl		590 ^{M}kl (15.5%)	
FUEL TYPE	SUPPLY (RESULT)	RATIO	SUPPLY (FORCAST)	RATIO
COAL	92.4 ^{M}ton	16.7	153 ^{M}ton	19.5
(DOMESTIC COAL)	(18.1 ^{M}ton)		(18.1^{M}∿20^{M}ton)	
(STEAMING COAL)	(21.3 ^{M}ton)		(66 ^{M}ton)	
NUCLEAR	15,700 MW	5.0	46,000 MW	11.3
NATURAL GAS	25.9 ^{M}kl	6.0	68.0 ^{M}kl	11.5
(DOMESTIC NG)	(2,200 ^{M}m^{3})		(7,300 ^{M}m^{3})	
(LNG)	(16.8 ^{M}ton)		(43.0 ^{M}ton)	
HYDRAULIC HYDRAULIC	19,000 MW	5.6	23,500 MW	5.0
PUMPING UP	10,800 MW		22,000 MW	
GEOTHERMAL	300 MW	0.1	6,000 MW	1.0
ADVANCED ENERGY OTHERS	0.7 ^{M}kl	0.2	15.0 ^{M}kl	2.5
PETROLEUM	285 ^{M}kl	66.4	290 ^{M}kl	49.1
(DOMESTIC OIL)	(0.5 ^{M}kl)		(1.9 ^{M}kl)	
(LPG)	(14 ^{M}ton)		(24 ^{M}ton)	
TOTAL SUPPLY	429 ^{M}kl	100	590 ^{M}kl	100

As this is prepared by taking into account the change of situation in recent years, i.e., economic stagnation, change of industry structure toward energy conservation, saving of energy consumption by individual citizens, international glut of oil, and subsequent drop of oil prices, it will serve as the guideline of overall energy balance in Japan over the years ahead.

As is shown in this table, the total energy demand of Japan in 1980 was 429 million kl on oil basis, two thirds of demand being covered by oil. About half the remainder was derived from coal, amounting to 92 million tons in coal weight. The forecasted total energy demand of ten years ahead, i.e. in 1990 comes to 590 million kl, where oil falls short of the half dropping to 49% while, on the other hand, coal increases to 153 million tons. The increase of coal takes place mainly in the type of steaming coal for the application of electric power generation and for other industries, particularly for the use as fuel for power generation.

(2) Increasing coal use for electric power generation

In Table 2 is shown the outlook of increase in power generation capacity by primary energy. Coal fired power plant capacity is estimated to increase sharply from 6 million KW in 1980 to 22 million KW in 1990. This indicates that there will be the construction rush of large-scale coal fired power plants in the 1980s, with Matsushima thermal power plant of Electric Power Development Co., Ltd. (EPDC) was the first to come. The total capacity expansion of coal-fired power generation plants will reach approximately 16 million KW and, as per present forecast, boilers employed for this purpose will be all of pulverized coal firing type.

TABLE 2. LONG TERM CAPACITY EXPANSION PROGRAM

FISCAL YEAR / ITEM	1981		1990	
Nuclear	16 GW	12 %	47 GW	22 %
Hydraulic	18	14	21	10
Pumping up	12	10	22	10
Coal	6	5	22	10
LNG	19	15	43	20
LPG	1	1	3	1
Other gas	3	2	2	1
Geothermal	0.1	0.1	1	1
Petroleum	55	42	50	24
TOTAL	130	100	211	100

(Electric Utilities' Long Term Plan, 1982)

2. Environmental regulations by the government and pollution control by electric power utilities.

(1) Environmental regulations by the government

While the remarkable growth of heavy and chemical industries was under way in Japan in the 1960s, environmental pollution typified by air pollution popped up as a social issue in the urban industrial districts. To cope with such situation, a law for restricting the discharge of waste flue gases was enacted in 1962 by the Japanese government for the first time in the country with a view of preventing the air pollution and thus the pollution control was initiated in earnest. Thereafter, extensive environmental restrictions including SOx, NOx, particulates, water quality of sewage and noises were imposed on the electric power industries by the Japanese government with increasing intensification. Further, the local governments normally conclude individual agreements with the power plant to impose still severer restrictions. In view of the scale enlargement of power plant, the total discharge quantity has also come to be limited in addition to the concentration limitation.

Consequently, the typical existing coal-fired power plant must comply with the very severe restrictions, for example 60 ppm for SOx, 150 ∿ 180 ppm for NOx and 50 mgr/Nm^3 for particulate emissions and same restrictions seem to be applied also to a new plants to be constructed.

(2) Pollution control by electric power utilities

1) Steps in terms of fuel

Coal was once occupying the major parts of the fuel for thermal power generation, but today wide varieties of fuels are used including heavy oil, crude oil, naphtha, NGL, LNG, LPG and coal. Conversion to heavy oil from coal or introduction of direct burning of crude oil, accelerated in 1960s was undertaken at first for the economic reason, but since the 1960s when air pollution problem, surfaced as a matter of great concern, (1) reduction of coal utilization (2) shift to lower sulfur content in connection with heavy and crude oils (3) introduction of light-fraction oils such as naphtha and NGL, and (4) introduction of gasious fuel were prompted as measures to curtail sulfur oxides, particulates and nitrogen oxides. The change of sulfur content in fuel for thermal power generation is shown in Table 3.

TABLE 3. THE CHANGE OF SULFUR CONTENT IN FUEL FOR THERMAL POWER GENERATION

(%)

ITEM \ F. YEAR	1967	'70	'73	'75	'77	'78	'79	'80
COAL			0.48	0.44	0.55	0.56	0.56	0.55
HEAVY OIL	2.24	1.56	0.76	0.84	0.80	0.84	0.87	0.81
CRUDE OIL	2.49	1.45	0.54	0.23	0.16	0.14	0.14	0.13
NAPHTHA	-	-	0.05	0.05	0.05	0.05	0.05	0.04
AVERAGE (OIL EQUIVALENT)	2.3	1.5	(0.65) 0.65	(0.33) 0.49	(0.24) 0.55	(0.20) 0.44	(0.20) 0.43	(0.19) 0.41

NOTE: ( ) AFTER FLUE GAS DESULFURIZATION UNIT

The drop of sulfur content in heavy and crude oils achieved as measures against sulfur oxides has been remarkable, sulfur content went down to the order of 0.4% as of 1980. This value is about one sixth of the value of 1967 and in respect of the value measured after flue gas desulfurization, sulfur content has been reduced to less than one tenth during these 13 years.

It is the general tendency that the drop of sulfur content causes also the drop of nitrogen content, resulting in lower NOx emission. The particulate emission could also be reduced. In this connection, power generation industries have introduced actively the heavy and crude oils with low sulfur content, but the drop of sulfur content has levelled off since 1977. This sulfur content value in the order of 0.4% could be regarded almost as the limit value from the nation-wide point of view.

2) Steps in terms of equipment

In this paragraph, explanation will be given in particular on equipment to prevent SOx, NOx and particulates emission. In Japan, a great number of equipment with excellent performance for all applications are already in continuous operation with high stability and reliability.

Today's leading type of flue gas desulfurization unit employs the wet process and existing units are mostly of wet type with sulfer removal efficiency of more than 90%. In this wet process sulfur oxides are absorbed in the absorption liquid and recovered as by-products after some chemical treatment. The major method is the lime (or limestone) gypsum process where by-products are collected in the form of gypsum.

Wet desulfurization, however, envolves such problems as the requirement of fresh water in enormous amounts and also the necessity of waste water treatment. This prompted the technical development of dry desulfurization process (SOx in flue gas is absorbed in activated carbon) of late and the large-scale demonstration plant test is to start from 1983.

Flue gas desulfurization units now in operation are listed in Table 4.

TABLE 4. FLUE GAS DESULFURIZATION UNITS IN JAPAN

(MARCH, 1981)

ELECTRIC POWER COMPANY	POWER STATION	BOILER UNIT		TYPE	CAPACITY		DATE OF OPERATION	FUEL
		UNIT NO.	POWER OUTPUT (MW)		GAS FLOW (10^3/Nm^3/h)	RATIO (%)		
HOKKAIDO	DATE	1	350	WET	260	25	11/'78	OIL
"	TOMATOATSUMA	1	350	"	610	48	10/'80	COAL
TOHOKU	AKITA	3	350	"	1,064	100	3/'78	OIL
"	HACHINOHE	4	250	"	380	50	4/'74	"
"	NIIGATA	4	250	"	380	50	10/'76	"
"	HIGASHINIIGATA	1	600	"	420	25	4/'77	OIL·GAS
"	NIIGATAKO	1	350	"	1,060	100	3/'79	OIL
TOKYO	KASHIMA	3	600	DRY	420	25	9/'72	"
"	YOKOSUKA	1	265	WET	400	50	3/'74	"
CHUBU	NISHINAGOYA	1	220	"	620	92	9/'73	"
"	OASEMITA	1	375	"	1,200	92	4/'76	"
"	"	2	375	"	1,200	92	6/'76	"
HOKURIKU	TOYAMASHINKO	1	500	"	750	50	10/'74	"
"	FUKUI	1	350	"	1,050	100	6/'75	"
KANSAI	AMAHIGASHI	1	156	"	475	100	12/'76	"
"	"	2	156	"	475	100	2/'75	"
"	KAINAN	4	600	"	400	25	3/'74	"
"	OSAKA	2	156	"	500	100	12/'75	"
"	"	3	156	"	500	100	3/'75	"
"	"	4	156	"	500	100	10/'76	"
CHUGOKU	MIZUSHIMA	2	156	"	310	64	4/'74	"
"	TAMASHIMA	2	350	"	1,600	100	3/'76	"
"	"	3	500	"	1,460	100	7/'75	"
"	SHIMONOSEKI	1	175	"	620	100	7/'79	COAL
"	"	2	400	"	1,210	100	9/'77	OIL
SHIKOKU	ANAN	[illegible]	450	"	1,260	100	8/'75	"
"	SAKAIDE	3	450	"	1,278	100	10/'75	OIL·GAS
KYUSHU	KARITA	2	375	"	[illegible]	50	11/'74	"
"	KARATSU	2	375	"	570	50	4/'76	"
"	"	[illegible]	500	"	[illegible]	50	7/'76	"
"	AINOURA	1	375	"	730	67	5/'76	"
"	"	2	500	"	730	50	10/'76	"
"	BUZEN	1	500	"	736	50	12/'77	"
"	"	2	500	"	750	50	6/'80	"
E.P.D.C.	TAKASAGO	1	250	"	894	100	2/'75	COAL
"	"	2	250	"	894	100	3/'76	"
"	ISOGO	1	265	"	876	100	3/'76	"
"	"	2	265	"	876	100	5/'76	"
"	TAKEHARA	1	250	"	852	100	2/'77	"
"	MATSUSHIMA	1	500	"	1,300	78	1/'81	"
SAKATA KYODO	SAKATA	1	350	"	1,120	100	10/'77	OIL
"	"	2	350	"	1,160	100	10/'78	"
TOYAMA KYODO	TOYAMA	1	250	"	750	100	10/'75	"
SHOWAHATSUDEN	ICHIHARA	5	75	"	219	100	5/'76	"
"	"	6	175	"	481	100	5/'76	"
MIZUSHIMA KYODO	MIZUSHIMA	5	156	"	612	100	10/'75	OIL·GAS
SUMITOMO KYODO	NIIHAMA	1	22.5	"	217.2	100	4/'77	OIL
"	"	3	156	"	450	100	9/'76	"
FUKUI KYODO	MIKUNI	1	250	"	750	100	9/'78	"
TOTAL		49	15,735.5					

In tackling with nitrogen oxides (NOx), one approach is to make use of such technique as to suppress the evolution of NOx in combustion process including two-stage combustion, flue gas mixing and the use of low NOx burners while the other approach is to use flue gas denitrification where NOx in flue gas is subjected to treatment. Both of these approaches are put into practical use. Especially regarding measures to prevent nitrogen oxides emission at coal-fired power plant, not only the suppression technique by means of combustion improvement is available for commercial use but also the process of treating the flue gas in denitrification equipment after removing particulates through an electrostatic precipitator at high temperatures is looked upon as feasible on commercial scale with expected efficiency of about 80%. Demonstration test of this process is under-way by a large-scale demonstration plant installed in EPDC's Takehara thermal power station. Table 5 shows the flue gas denitrification units already installed and presently operating.

TABLE 5. FLUE GAS DENITRIFICATION UNITS IN JAPAN

(MARCH, 1981)

ELECTRIC POWER COMPANY	POWER STATION	BOILER UNITS		CAPACITY		DATE OF OPERATION	FUEL
		UNIT NO.	OUTPUT (MW)	GAS FLOW ($10^3 Nm^3/h$)	RATIO (%)		
HOKKAIDO	TOMATOATSUMA	1	350	280	22	10/'80	COAL
CHUBU	CHITA	2	375	1,036	100	1/'77	OIL
"	"	4	700	1,960	"	3/'80	OIL·LNG
"	"	5	700	1,910	"	3/'78	LNG
"	"	6	700	1,910	"	4/'78	"
"	SHINNAGOYA	3	220	650	"	9/'80	OIL
"	NISHINAGOYA	4	375	1,000	"	3/'81	OIL·NAPHTHA
"	"	6	500	1,340	"	7/'80	"
KANSAI	KAINAN	1	450	300	"	2/'80	OIL
"	HIMEJI NO. 1	4	156	490	"	10/'80	"
"	AMAGASAKI HIGASHI	1	156	470	"	10/'80	"
"	"	2	156	470	"	4/'80	"
"	AMAGASAKI NO. 3	2	156	470	"	7/'80	"
"	"	3	156	450	"	2/'80	"
"	SAKAIKO	1	250	800	"	9/'80	OIL·LNG
"	"	5	250	800	"	8/'80	"
"	"	6	250	800	"	7/'80	"
"	OSAKA	1	156	530	"	10/'78	OIL
"	"	3	156	530	"	9/'80	"
"	"	4	156	530	"	6/'80	"
"	TANAGAWA	4	156	520	"	3/'81	"
"	KASUGADE	1	156	470	"	5/'81	"
CHUGOKU	KUDAMATSU	2	375	1,510	"	9/'79	OIL·NAPHTHA
"	"	3	700	1,900	"	9/'79	OIL
	SHIMONOSEKI	1	175	550	"	3/'81	COAL
KYUSHU	SHINKOKURA	3	600	1,690	"	9/'78	LNG
"	"	4	600	1,690	"	6/'79	"
EPDC	TAKEHARA	1	250	850	"	8/'81	COAL
TOTAL		28	9,380				

For the purpose of particulates suppression measures, almost all the thermal power plants, except those using high-grade dust-free fuel such as LNG, are equipped with high-performance electrostatic precipitators with resultant dust collection efficiencies exceeding the designed value.

Flue gas from the coal-fired power stations contains fairly large amounts of dusts, in constrast to the oil-fired, due to high ash content (15 ∿ 20%) in coal. Therefore, electrostatic precipitators are installed to effectively remove the dusts, and now their average dust collection efficiency is more than 99%. Also, the wet desulfurization equipment serves as a means of removing dusts, thus enhancing the removal effects further coupled with the electrostatic precipitator.

At present, the development of high-temperature electrostatic precipitation technology is under way with the aim of application to wide coal varieties while, on the other, band, the development of high-efficiency dust collection technique such as the method of using bag-filters is also going on with the aim to obtain higher dust collection efficiency.

3. Significance of developing the FBC boiler for power generation businesses

(1) Characteristics of the FBC boilers

The FBC boilers are those that are designed to recover combustion heat developed from fluidized bed combustion through heat transfer surface located at both the fludized bed and convection sections. Fluidized medium consists normally of solid particle mixtures of coal, coal ashes and limestone.

Blowing of air to this fluid medium mass through the air distributor causes the solid particles to suspend in the air stream and then to form a fluidized bed between certain flow speed ranges as if liquid is boiling.

The fulidized bed has the combined functions of combustion furnace and flue gas treatment unit as desulfurization and denitrification reactions of sulfur oxides and nitrogen oxides produced by combusion are taking place along with combustion reaction within this space.

Characteristics of the boilers of this type are as enumerated below:

1) Homogeneous, stable, and low temperature combustion is attained, though subject to design, with the bed temperature kept between 800 ∿ 900°C, in contrast to pulverized coal combustion whose maximum flame temperature reaches to as high as 1500°C.

2) Coal is burned at a temperature below its ash melting

point, thus avoiding slugging and fouling by ashes, the problems often encountered in design and operation of pulverized coal-fired boilers, and therefore this ensures wide application to many coal varieties.

3) Reduction of NOx formation can be expected owing to low temperature combustion.

4) Size-reduction of boilers can be expected owing to high heat conductivity within the fluidized bed.

5) Combustion is of the type yielding less amounts of sulfur oxides as incombustible sulfur in coal is not converted to oxides and remains in the bed on account of the low temperature combustion.

6) Desulfurization effect can be expected by the use of limestone as fluidized medium.

(2) Significance for power generation business

It will be described here what meaning the aforementioned characteries of the FBC boiler has for utilities in Japan. To sum up, the FBC boiler is regarded as possessing essentially the promissing features which can be beneficial to special application in Japan though it is too early to form a clean judgement as the development of such boilers is still in the pilot plant (steam evapolation capacity: 20 t/h) operation stage as will be mentioned later, leaving much to future test results.

1) The FBC boiler may fit better than pulverized coal-fired boiler when coal has a low ash melting temperature, a poor pulverizing property or some special property because of low temperature combustion characteristics and capability of burning comparably lage size of coal of the FBC boiler.

   As the domestic coal production is only about 20 million tons per year, Japan has to depend upon imports from virtually all foreign countries in coal supply which, as mentioned before, is bound to keep growing. Therefore it is essential for Japan to develop the combustion technology that suits to all sorts of coals without being restricted to only such coal that is presently imported or that is planned to be imported. Under these circumstances, the FBC boiler is viewed as one of the candidate boilers fitted to burn easily such coal as is difficult to burn in the conventional pulverized coal-fired boiler.

2) The FBC boiler is not likely to require so much expenses for flue gas desulfurization and denitrification as in the case of the pulverized coal-fired boiler due to desulfurization and denitrification reactions in the furnace.

   In some cases, flue gas desulfurization and denitrification may even be omitted for the reason that incombustible sulfur does not give off to the flue gas, that lime stone acts as desulfurization reagent, and that low temperature combustion produces low level of NOx. If it is proved to be true, economic advantage of the FBC boiler would be enormous. In Japan, however, restrictions of SOx and NOx are so strict that they are narrowly cleared by desulfurization and denitrification units which have reached near perfect level. Moreover, the violation, however temporary it may be, has the danger of resulting in the punishment of power plant operation stoppage which is fatal to power generation businesses. Such being the case, we, Japanese electric power utilities, would be most prudent and cautious when we build a FBC boiler power plant not for research and development but for real business. A FBC boiler power plant without desulphurizing and denitrificating equipment is surely our ideal target, but it can not be judged now whether or not such a plant will be realized in Japan since it will depend upon locality of the plant site, possible results of research and development and so on. However, thanks to inherent nature of FBC boiler, we could say that the boiler FBC can be classified as relatively low-pollution type boilers since costs of flue gas desulfurization and denitrification with the FBC boiler seem to be much lower as compared with pulverized coal-fired boilers.

3) It is possible to make the boiler compact in principle.

Therefore possible decrease in boiler costs and plant area are the another attractive points. On the other hand, the likely sophistication of the coal supply system obscured the prospect if the FBC boiler can be actually reduced in plant size.

To summarize, what is most expected of the FBC boiler by Japanese utilities lies in the superior adaptability to special quality coal in comparison with pulverized coal-fires boilers. On the basis of this conclusion, EPDC has decided to participate in the project of 20 t/h pilot plant at its Wakamatsu Power Station with collaboration of the Japan Coal Mining Research Center, Kawasaki Heavy Industries Ltd. (KHI) and Babcock-Hitachi K.K. (BHK) and is carrying out the test operation now. The outline of the project is explained below.

II. 20 t/h FBC boiler pilot plant

1. Outline of the project

(1) Brief history

This project is being developed jointly by the Japan Coal Mining Research Centre, Electric Power Development Co., Ltd. (EPDC), Babcock-Hitachi K.K. (BHK), and Kawasaki Heavy Industries Ltd., (KHI) under subsidy by the Japanese government.

In 1978 and 1979, a preliminary study using a bench scale experimental unit and a feasibility study for a 500 MW power generation unit were carried out. This resulted in clarifying the fact that the FBC boiler has better characteristics for pollution control (it has possibility to eliminate a flue desulfurization unit and devitrification unit) than conventional pulverized coal firing boilers and, furthermore, has many advantages as a boiler system such as wide range applicability to various kinds of coals, economic advantages, etc.

The whole program of the fluidized bed boiler development is shown in Table 1. Following to the bench scale experiments, a pilot plant with a 20 t/h evaporation capacity were constructed in the Wakamatsu Thermal Power Plant of EPDC for the purpose of demonstrating and determining the most suitable operating conditions of the FBC boiler.

The detail design, manufacture and installation of the pilot plant were assigned as follow:

Babcock-Hitachi K.K.:

Main boiler unit, start-up burner equipment, feed water equipment and condenser, dust collector, civil engineering and building construction.

Kawasaki Heavy Industries, Ltd.:

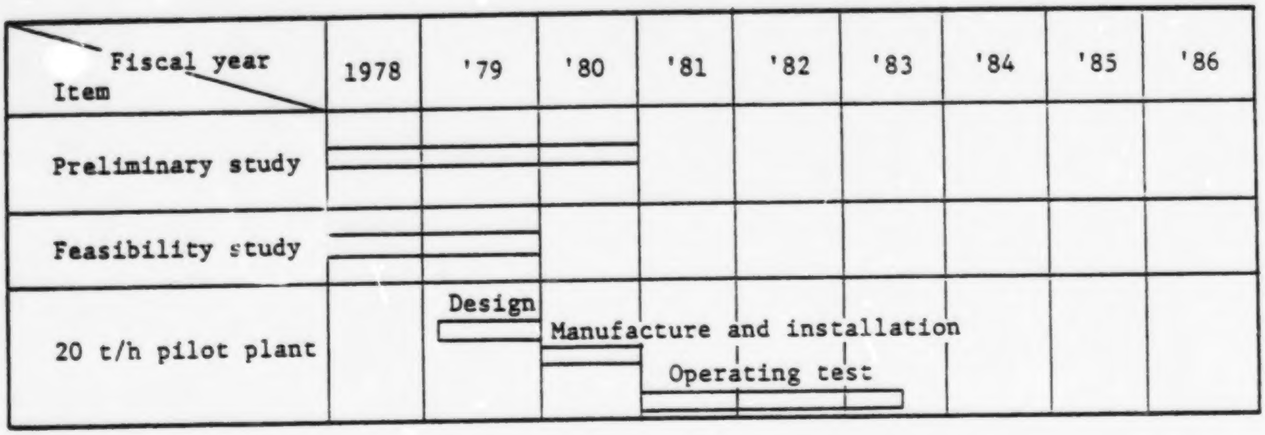
Coal and limestone supply equipment, draft equipment, ash handling equipment, electrical equipment and instrumentation.

This pilot plant was designed in fiscal year of 1979 and its manufacture and installation were completed in fiscal year of 1980.

In April 1981, the plant was put into an initial operation.

It is scheduled to operate until mid 1983. During fiscal year of 1981, a desulfurizing reagent (lime stone) regeneration unit and high performance dust collectors system were add.

TABLE 1. FBC BOILER DEVELOPMENT PROGRAM IN JAPAN



(2) Test Items

The test and research using this pilot plant are planned mainly for the following:

1) Demonstration of low pollution control
2) Measures to reduce the quantity of desulfurizing agent
3) Demonstration of controllability of the fluidized bed boiler
4) Demonstration of reliability of the fluidized bed boiler
5) Suitable types of coal
6) Demonstration of performance of the dust collector

2. Pilot plant discription

(1) Basic construction

The pilot plant is a FBC boiler with 20 t/h evapolation capacity. The basic construction is as follows:

1) The FBC boiler consists of a main bed cell (MBC) and a carbon burn-up cell (CBC).

2) The design was made so that various imported coals and low grade coals, in addition to the design coal which will be described later, can be burned.

   Crushed coal is used as a feed coal. Before feeding, the coal is pretreated - drying, crushing screening, etc. Coal feeding is done basically by;

   Fine grain coal : Fed to the bottom of the hearth through a pneumatic conveyer.

   Coarse grain coal : Sprinkled over the fluidized bed by a spreader.

   The required total quantity of coal can be fed, by either one of methods.

3) Natural limestone whose sizing has been completed at the mine is used as a desulfurizing reagent. The reagent is fed through a pneumatic conveyer.

4) A multi-cyclone is installed at the outlet of the MBC. The design was made so that the collected ash can be reburned in MBC or CBC.

5) A balanced draft system is used.

6) MBC was designed so that it can be divided into two parts.

7) The position of heating surfaces in the freeboard of

MBC can be changed. The duct connected to the rear flue can be removed to ease a change in the height of the freeboard.

8) The hot air generator is used for starting up the boiler.

9) Steam generated by the boiler is condenced by an air condenser. The water can be reused.

10) The discharged ash is wetted and transferred to the ash yard to be discarded.

11) In 1982, the following expansion or modification has been made.

    1 Desulfurizing reagent regeneration unit (commonly usable for limestone and synthetic desulfurizing reagent) was added.
    The unit was modified so that bed slumping can be made.

    2 Test dust-collectors
    Design dust discharge quantity ..... 10 mg/Nm^3,
    Gas volume .... approx. 1,000 N^3/h

(2) Design conditions

1) Main boiler specification

Boiler type:	Natural and forced circulation type drum boiler (indoor type)

Evaporation:	20 t/h
Steam pressure:	60 kg/cm^{2}G at the outlet of the superheater
Steam temperature:	540°C at the outlet of the superheater
Feedwater temperature:	133°C at the inlet of the economizer
Boiler efficiency:	87.37% (high calorific value base)
Fuel consumption:	2,450 kg/h (wet coal base)
Calorific value:	7,100 kcal/kg (higher heating value, dry) 6,603 kcal/kg (higher heating value wet)
Combustion gas volumes:	20,293 Nm^3/h (wet)

2) Target values for air pollutant discharge

SOx : 95% desulfurization (for coal containing 3%S)

NOx : 60 ppm (O_2 6% equivalent, for coal containing 1%N)

3) Properties of design coal: Refer to Table 3.

4) Desulfurizing reagent: natural limestone and synthetic desulfurizing reagent

TABLE 2. COAL PROPERTIES

Type of coal			Design coal
Dry coal high calorific value (kcal/kg)			7100
Surface moisture			7.0
Proximate analysis	Moisture	(%)	2.8
	Ash	(%)	9.5
	Volatile matter	(%)	28.5
	Fixed carbon	(%)	59.2
Ultimate analysis	C	(%)	73.8
	H	(%)	4.0
	N	(%)	0.8
	O	(%)	11.0
	Total sulfure	(%)	0.8

(3) Plant outline

Fig. 1 shows a picture of the plant model. Flow diagram of the plant and plot plan are shown Fig. 2 and Fig. 3.

1) Boiler

Fig. 4 shows a section of the boiler structure.

(a) MBC consists of the combustion furnace which is composed of a natural circulation membrane water wall and the refractory wall rear flue.

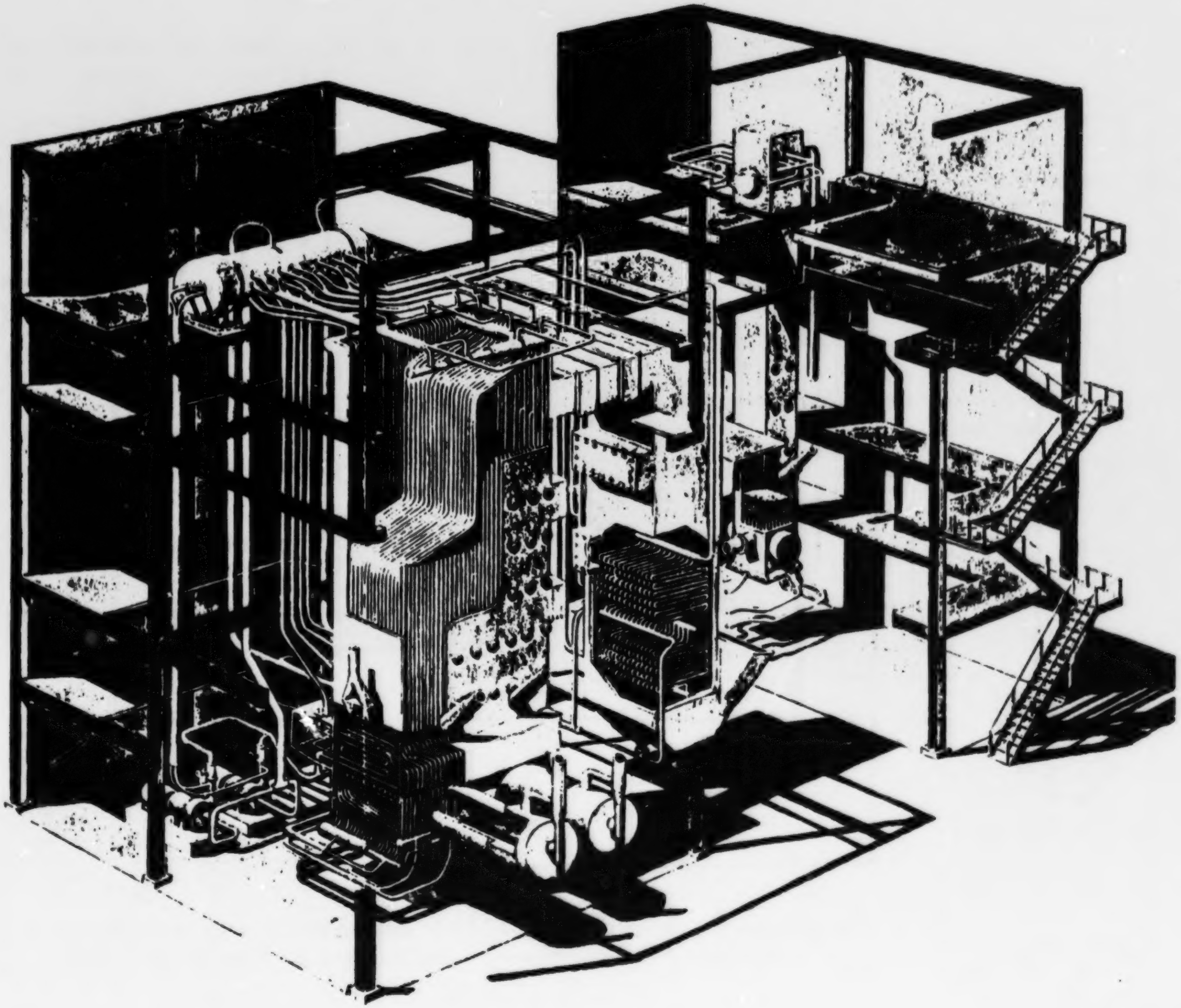


FIG. 1. 20t/h FBC BOILER PILOT PLANT

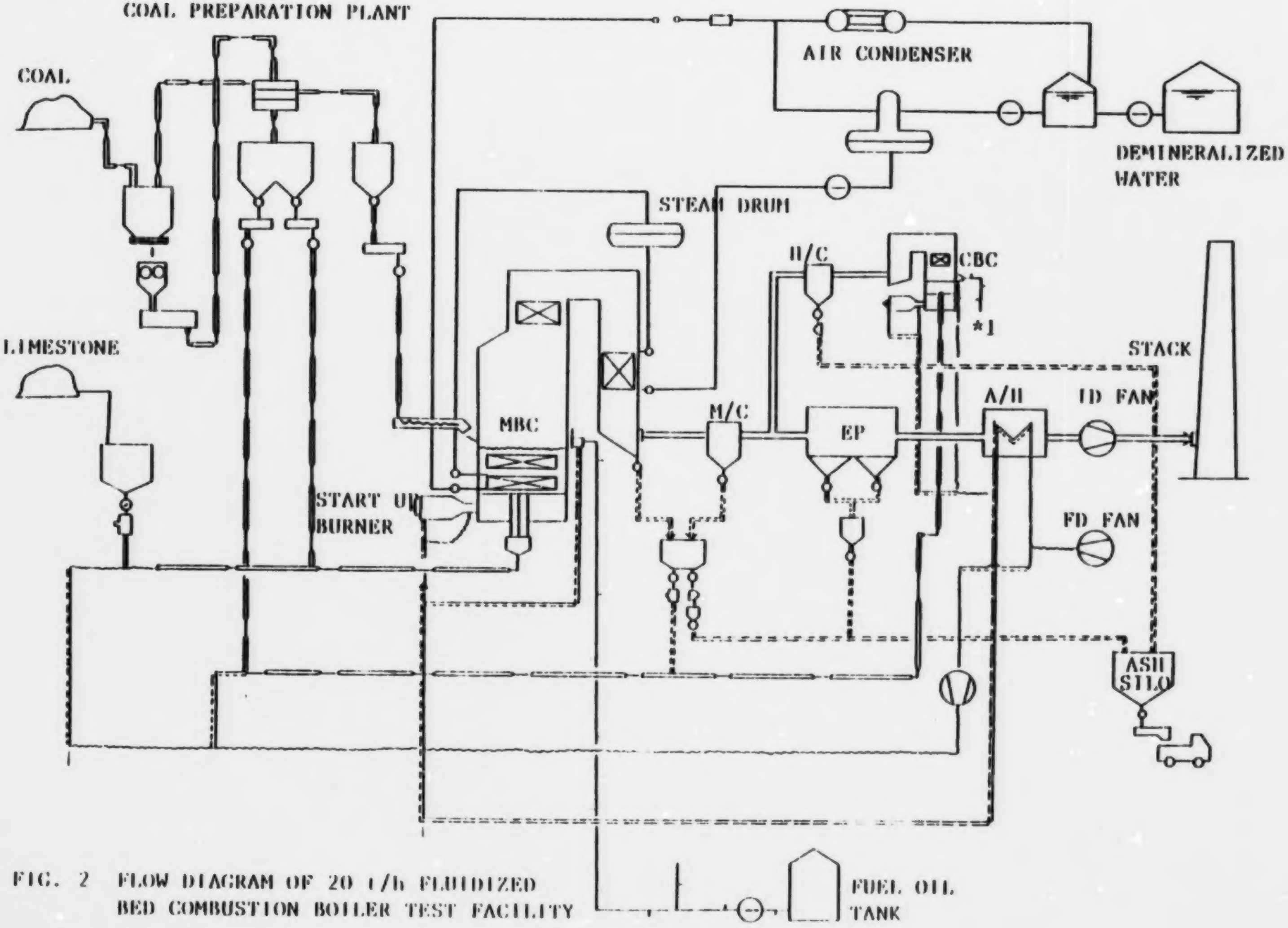
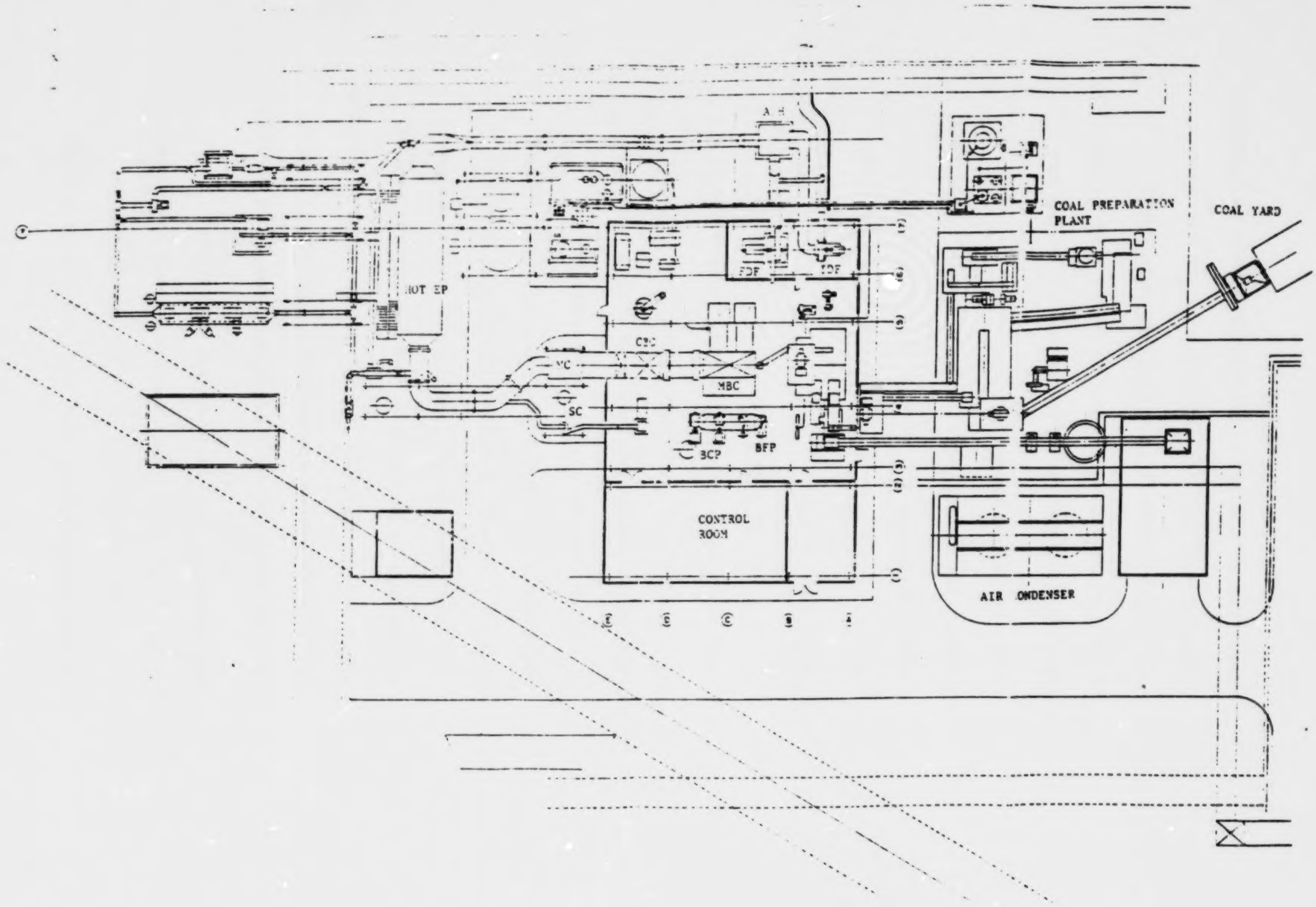

COAL PREPARATION PLANT
COAL
LIMESTONE
AIR CONDENSER
DEMINERALIZED WATER
STEAM DRUM
H/C
CBC
*1
STACK
MBC
M/C
EP
A/H
ID FAN
START UP BURNER
FD FAN
ASH SILO
FUEL OIL TANK

FIG. 2 FLOW DIAGRAM OF 20 t/h FLUIDIZED BED COMBUSTION BOILER TEST FACILITY


A H
COAL PREPARATION PLANT
COAL YARD
HOT EP
FDF
IDF
CBC
VC
MBC
SC
BCP
BFP
CONTROL ROOM
AIR CONDENSER
(1)
(2)
(3)
(5)
(6)
(7)
E
D
C
B
A

In the fluidized bed with a 2.17 m x 4.34 m area, the forced circulation type (by the boiler circulating water pump) evaporator and the primary and secondary superheaters are installed.

The fluidized bed is divided into two parts so that one side operation can be done. The specification (material, dimensions, etc.), layout and construction of the heating surfaces in the bed are designed so that they can meet the abovementioned requirement. Outside the bed, the evaporator and economizer are installed. This evaporator, as shown in Fig. 5, can be removed to the tower space of the combustion furnace or rear flue. This, together with a change in the installation level of the duct connecting to the rear flue, enable the test for a change in free board conditions to be conducted.

In the freeboard of the combustion furnace, two stage combustion air feeding ports (8 rows x 5 stages) are installed to enable various comparison tests to be conducted.

The air distribution plate in the fluidized bed bottom is made from a membrane wall. The fluidizing air nozzle, feeding nozzle for pneumatically conveyed coal and ash recycling nozzle are also installed in the bed. The coarse grain coal feeding

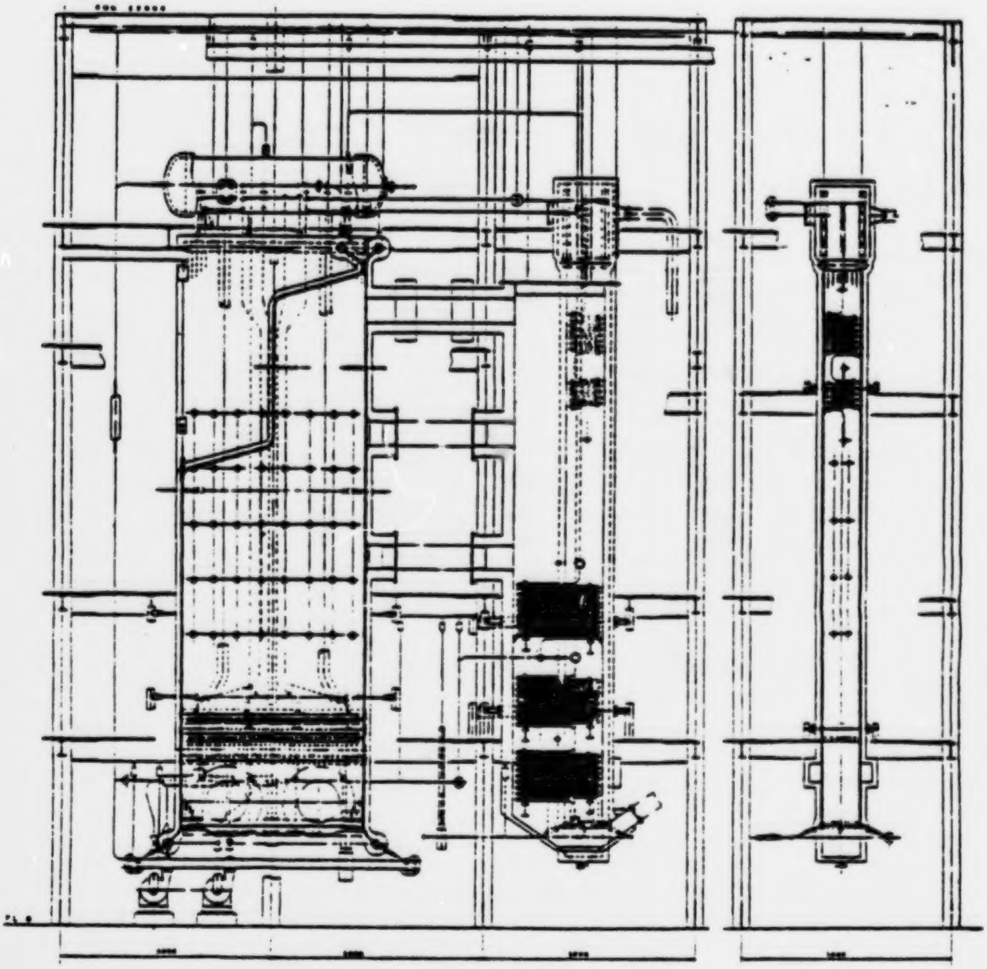


FIG. 4. SECTIONAL SIDE VIEW OF THE MBC AND CBC

port for the spreader is installed in the upper part of the fluidized bed front wall.

(b) CBC is composed of a natural circulation water wall (0.91 m x 0.91 m). In the freeboard of the CBC, a economizer is installed. The air distribution plate is made from heat-resistant steel plates (with refractory).

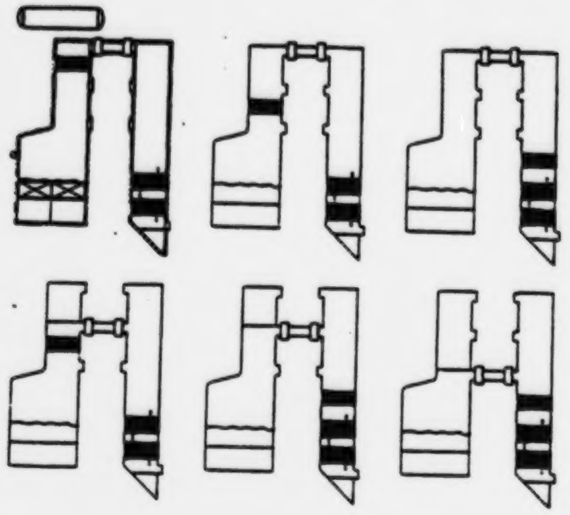


FIG. 5. 20 t/h FBC BOILER TEST MODULE

(c) Gas oil is used as a starting fuel for MBC and CBC. A hot air generator is installed in the wind box and, furthermore, an overbed burner is also installed.

(d) The level of the bed overflow is variable and the height of the fluidized bed is also variable. Overflow ash is cooled by an air cooler separately installed, then weighed and discharged into an ash storage bin installed below the boiler. This equipment is installed at both MBC and CBC.

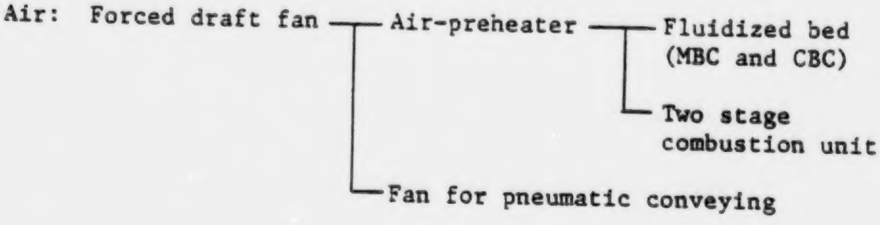
(e) To monitor and measure the temperature distribution in the fluidized bed and the temperature behavior in the major parts of the boiler, a number of thermocouples and the data processor are installed to be effectively used to evaluate and analyse test operation conditions.

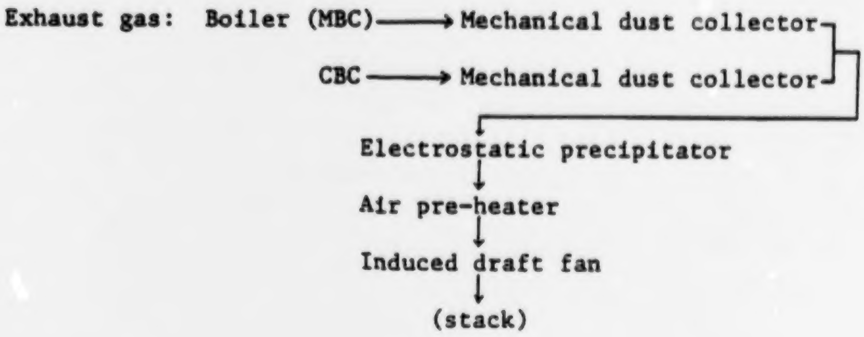
2) Draft fans

The draft system of this boiler is a balanced type. Air which has been pressurized with a forced draft is heated with the air-preheater, then enters the wind box of MBC and CBC for combustion (fluidizing air). A part of the air delivered from the fan is re-routed and pressurized (by the primary air fan) for use to convey feed coal and limestone.

Exhaust gas from MBC passes the economizer and the dust contained in it is collected by the dust collector. Then, the dust is further collected by an electrostatic precipitator. The gas is, then, sucked by a fan and discharged into the atmosphere through a stack.

Exhaust gas from CBC is sent to the electrostatic precipitator and joins the gas from MBC.


Air:
Forced draft fan
Air-preheater
Fluidized bed (MBC and CBC)
Two stage combustion unit
Fan for pneumatic conveying


Exhaust gas:
Boiler (MBC)
Mechanical dust collector
CBC
Mechanical dust collector
Electrostatic precipitator
Air pre-heater
Induced draft fan
(stack)

3) Coal and limestone feeder

The coal charged into the feed coal hopper is temporarily stored in the feed coal bunker and sent to the dryer to remove moisture, then crushed and screened for classification into fine grain and coarse grain coal.

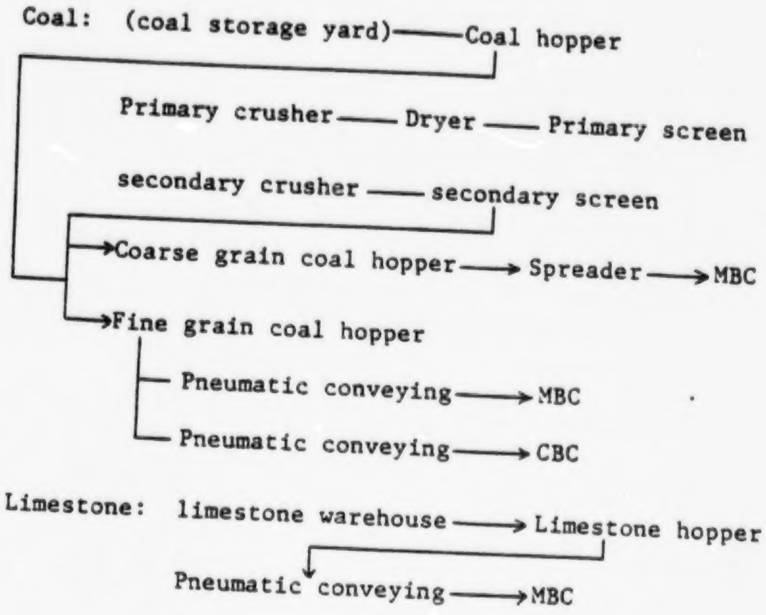
Coarse grain coal is sent to MBC and sprinkled over the fluidized bed by the spreader installed in the front wall of the freeboard.

Fine grain coal is sent to MBC (and CBC, as necessary) through pneumatic conveying and fed into the fluidized bed from the lower part of it through a coal feeding pipe.

The coal dryer is of a indirect steam heating type.

Coal is crushed in two stages before drying. The primary crushing is done by a roller and secondary crushing is also done by a roller, but an impeller crusher can be used for the crushing test.

Limestone whose grain size has been adjusted at the mine is used and supplied into MBC together with fine grain coal through pneumatic conveying.


Coal: (coal storage yard) — Coal hopper
Primary crusher — Dryer — Primary screen
secondary crusher — secondary screen
→ Coarse grain coal hopper → Spreader → MBC
→ Fine grain coal hopper
Pneumatic conveying → MBC
Pneumatic conveying → CBC
Limestone: limestone warehouse → Limestone hopper
Pneumatic conveying → MBC

4) Instrumentation

The instrumentation of this plant consists of the boiler control system, centralized operation monitoring system and data processing system (refer to Fig. 6).

For the boiler control system, the decentralized digital instrumentation (decentralized type digital controller, sequence controller, etc.) is used to achieve the adjustment with the host system.

The system is designed so that the composition of complex circuits which are impossible to use in an analog mode can be achieved. Since the circuit can be

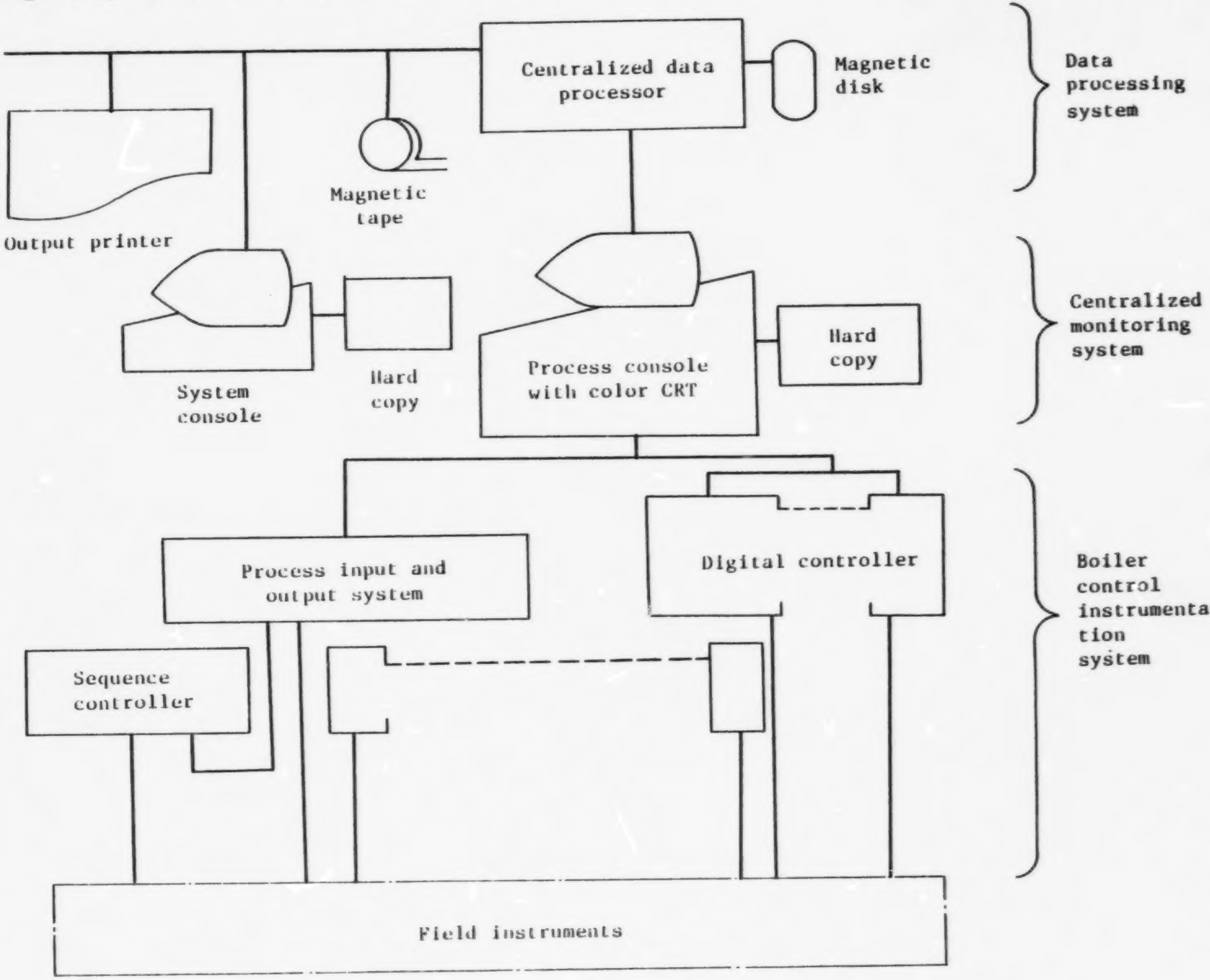

Centralized data processor
Magnetic disk
Data processing system
Output printer
Magnetic tape
System console
Hard copy
Process console with color CRT
Hard copy
Centralized monitoring system
Process input and output system
Digital controller
Sequence controller
Boiler control instrumentation system
Field instruments

FIG. 6. INSTRUMENTATION SYSTEM

changed by only a change in the software at the site, changes in the hardware and wiring can be minimized. Furthermore, the system is very flexible to change depending on various test conditions. Since a decentralized controller is used, the extent of failure propagation, which has been a problem for conventional digital instrumentation, has been greatly improved when compared with analog instrumentation.

5) Ash handling equipment

Ash discharged from the overflow pipe of MBC and CBC is cooled and sent to the overflow tank, then sent to the ash storage silo by the pneumatic conveyer system. Ash discharged from the hopper located blow the economizer for MBC and the mechanical dust collector for MBC is cooled and stored temporarily in the intermedicate hopper.

The intermediate hopper is connected with three line systems - the ash supply line to CBC, ash recycle line to MBC and discharge line to the ash storage silo. Any of these three lines can be selected depending on the test purpose.

Ash discharge from the electrostatic precipilator and mechanical dust collector for CBC is sent to the surge tank, then sent to the ash storage silo by the pneumatic conveyer system.

The humidifier which is installed at the outlet the ash storage silo humidifys ash when it is loaded on a truck to prevent ash from flying.

6) Regeneration unit for desulfurizing reagent

Capacity of the regeneration unit is adequate for all desulfurizing agent of 20 t/h pilot plant. The flow diagram is shown in Fig. 7.

(a) The reactor is composed of refractory wall. (Fig. 8)

(b) Outlet gas from the reactor passes to the desulfurization plant and is mixed with the main flue gas.

(c) Regenerated reagent is cooled and sent to hopper by pneumatic conveying.

7) High performance dust collector system (Test collectors)

The system consists of a bag-filter, an electristic precipitator and a granular-filter.

Gas capacity of each collector is about 1,000 Nm^3/h.

The flow diagram of the system is shown in Fig. 9.

(a) Test gas is drawn from the air heater outlet duct, and passes through the test dust collecters.

(b) Independent operation, or two collectors in parallel can be operated at the same time if necessary.

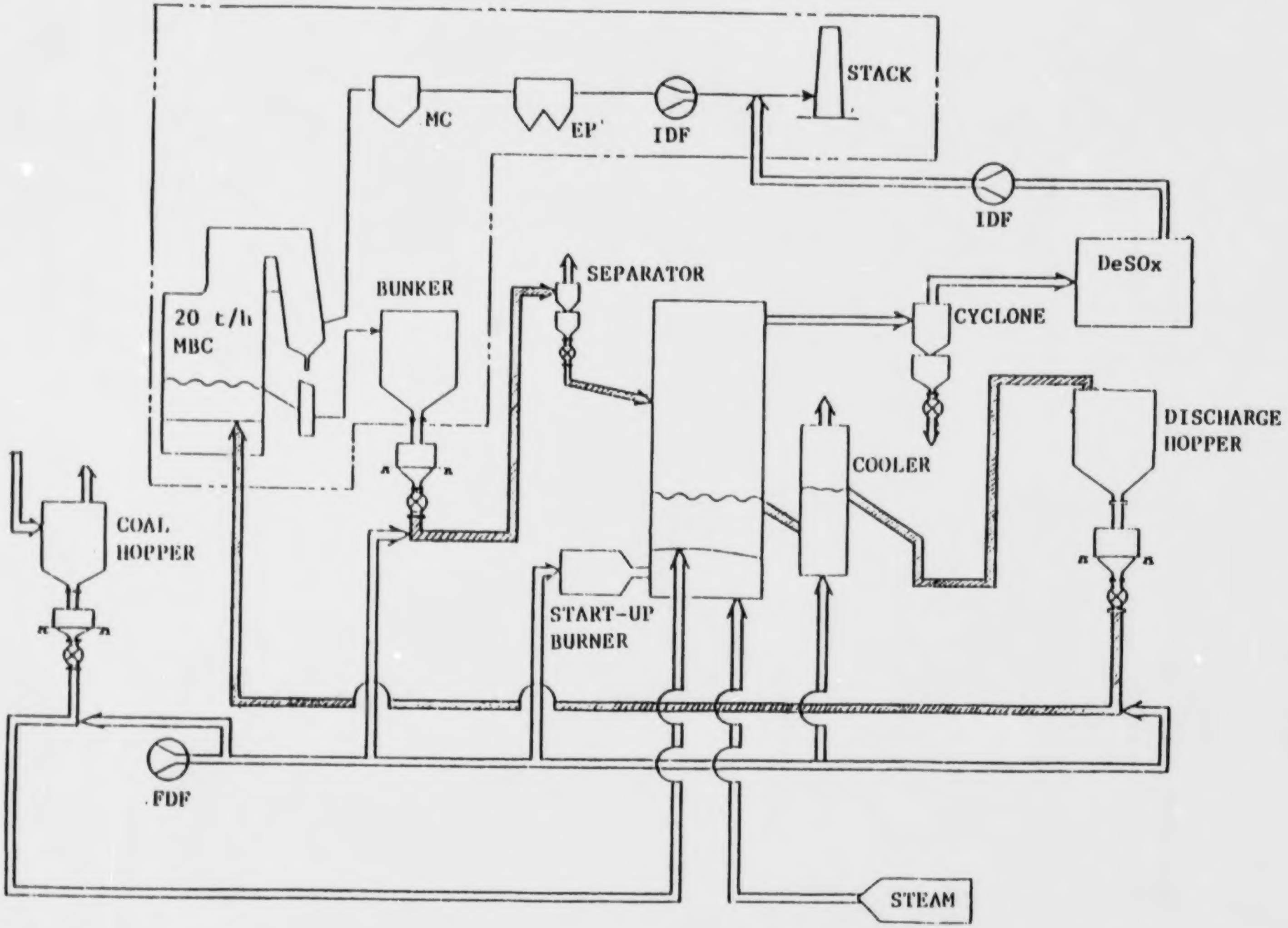

STACK
MC
EP
IDF
IDF
DeSOx
SEPARATOR
BUNKER
20 t/h
MBC
CYCLONE
DISCHARGE
HOPPER
COOLER
COAL
HOPPER
START-UP
BURNER
FDF
STEAM

FIG. 7 FLOW DIAGRAM OF REGENERATION UNIT

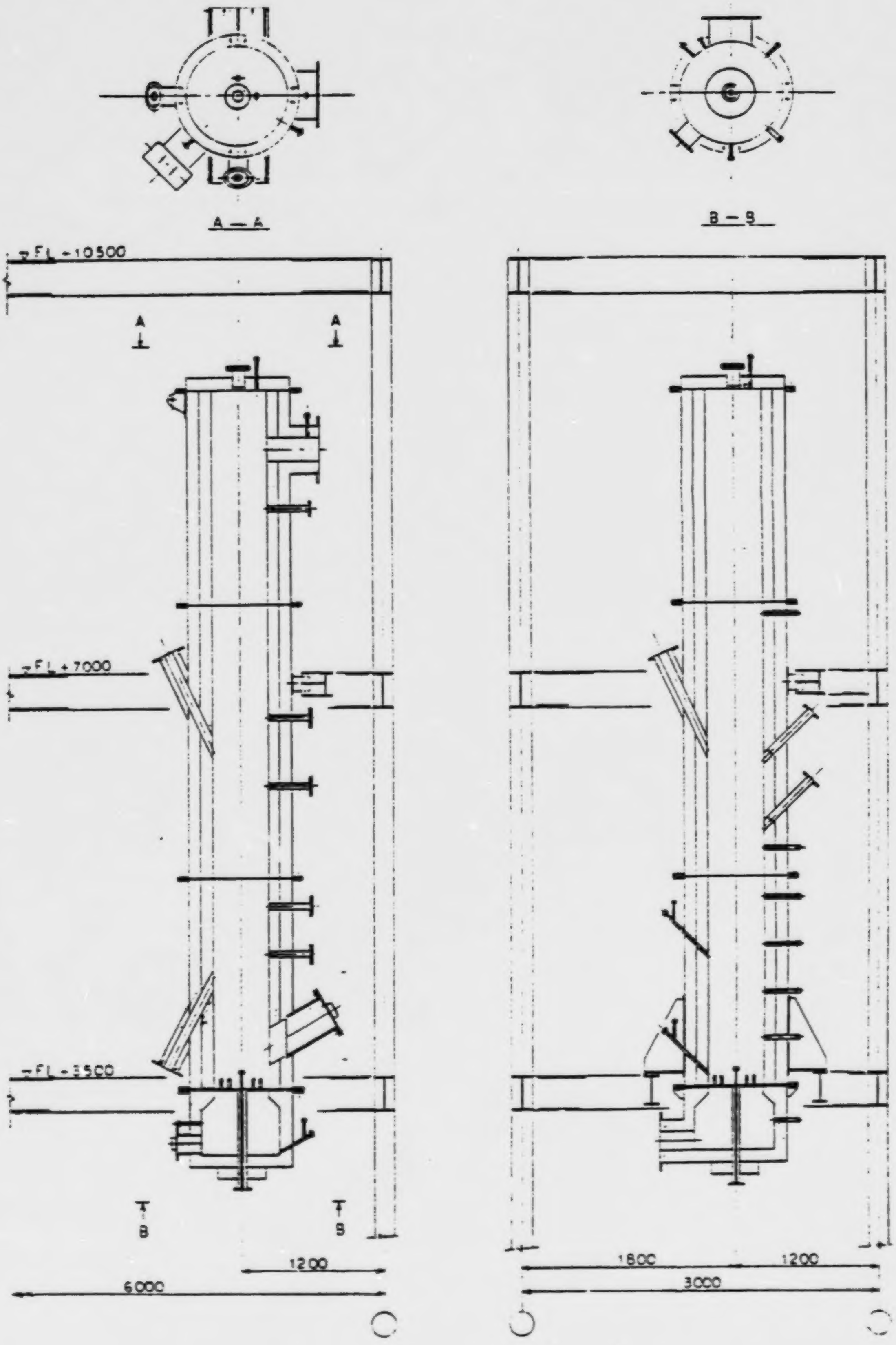

A — A
B — B
▽FL +10500
A
A
▽FL +7000
▽FL +3500
B
B
1200
6000
1800
1200
3000

FIG. 8 REACTOR OF REGENERATION PLANT

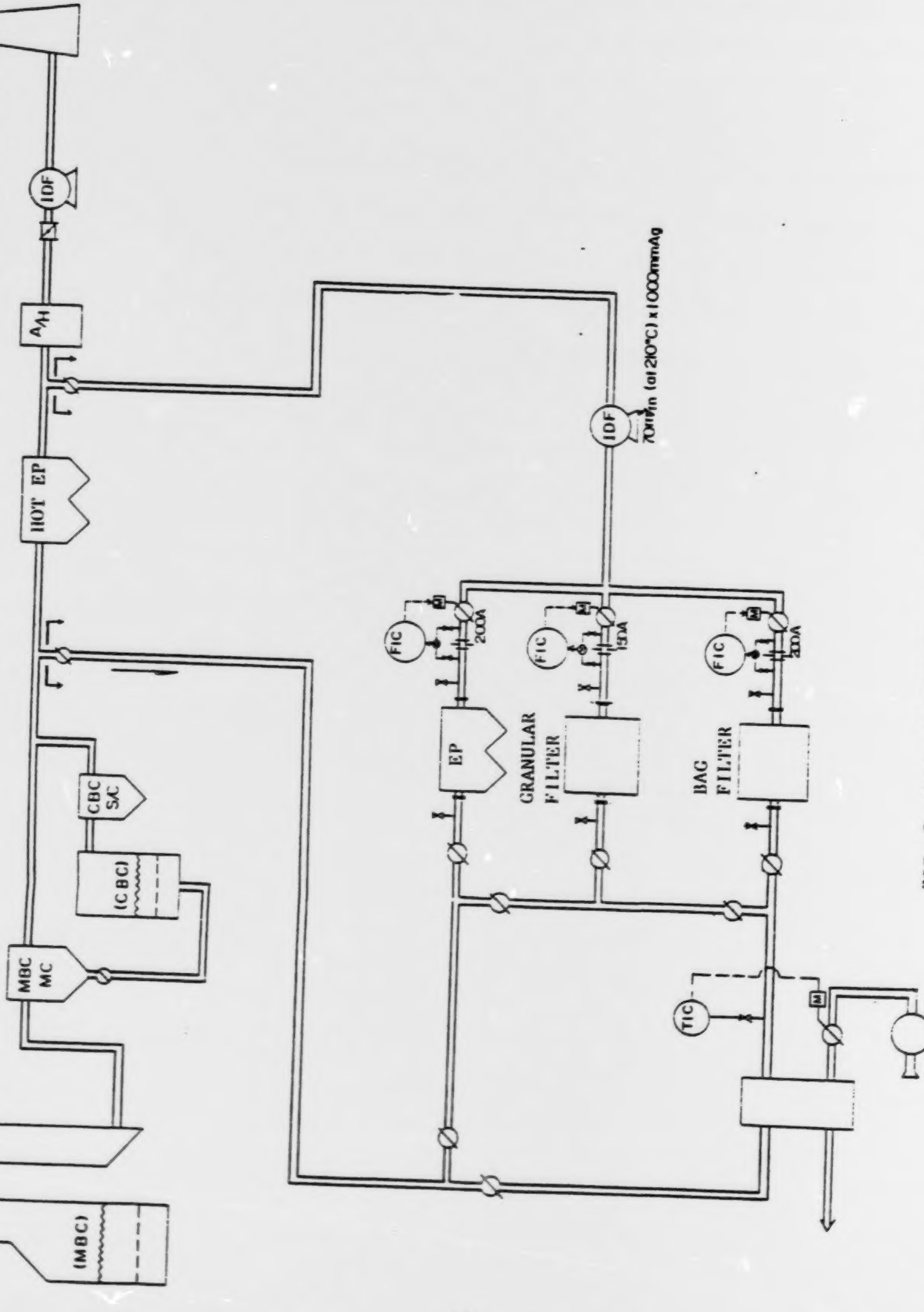

IDF
A/H
HOT EP
CBC S/C
(CBC)
MBC MC
(MBC)
IDF
70m³/min (at 210°C) x 1000mmAq
FIC
200A
FIC
150A
FIC
200A
EP
GRANULAR FILTER
BAG FILTER
TIC

FIG. 9 FLOW DIAGRAM OF TEST DUST COLLECTORS SYSTEM

(c) The system has a gas cooler so that inlet gas temperature can be controlled for the each dust collector.

8) Construction

Construction schedule of the pilot plant is shown Table 3. In fiscal year of 1980, the main boiler facility were completed and in fiscal 1981, the desulfurizing agent regeneration unit and the test dust collectors system were manufactured and installed.

TABLE 3. CONSTRUCTION SCHEDULE

DATE / ITEM	1980 7	8	9	10	11	12	1981 1	2	3	11	12	1982 1	2	3
Foundation	▨	▨	▨	▨	▨									
Buildings					▨	▨	▨	▨	▨					
Boiler Aux. Equipment				▨	▨	▨	▨	▨	▨					
Instrumentation						▨	▨	▨	▨				▨	▨
Regeneration Plant											▨	▨	▨	
Test Dust Collectors												▨	▨	▨

3. Test plan and schedule

Fig. 10 shows the development areas of the FBC boiler. In accordance with figuars, a test plan and schedule had been made. This was shown in Table 4 and 5. A test plan and schedule, as for the regeneration unit and test dust collectors system are planning.

An outline of the whole schedule is shown in Table 6.

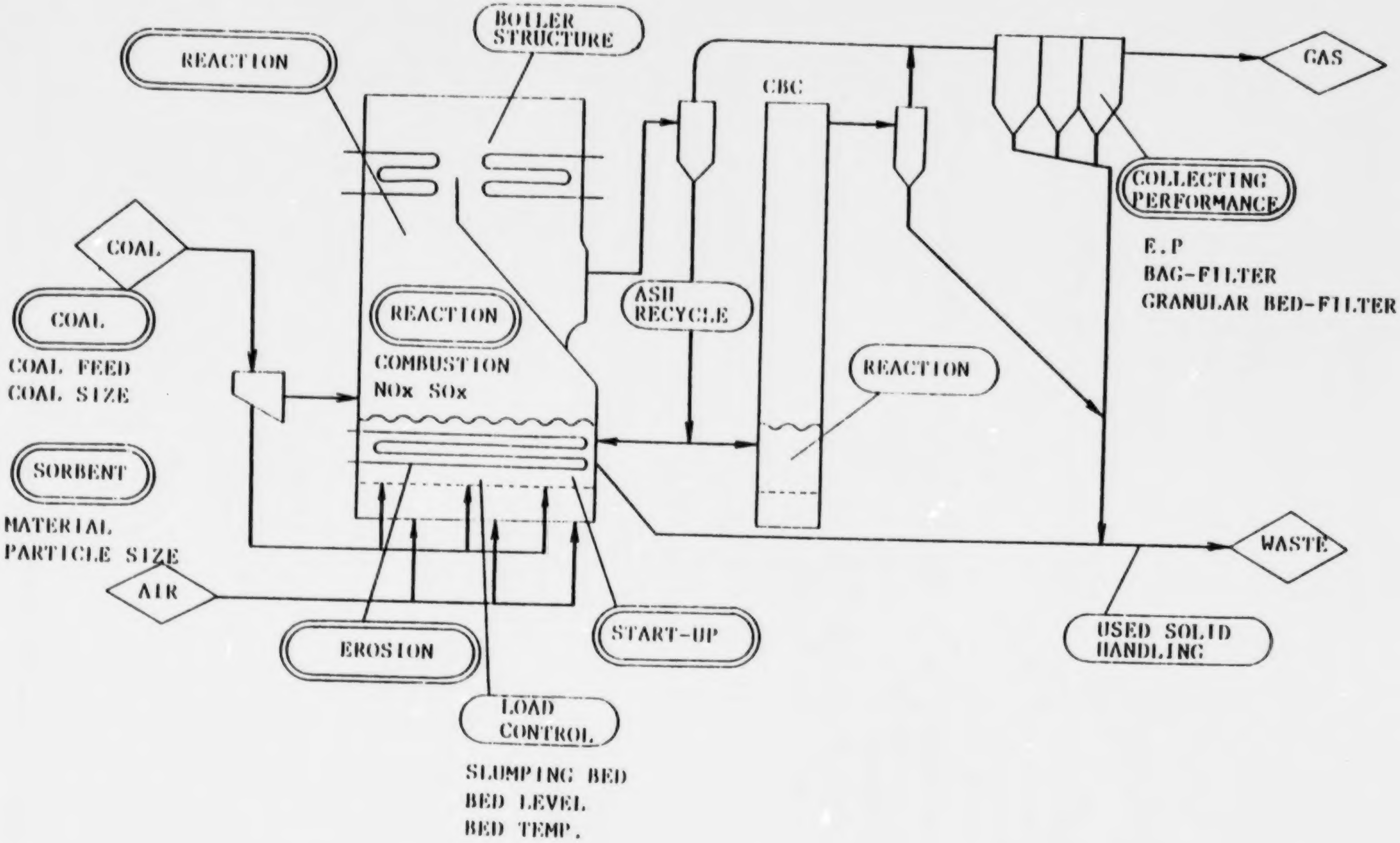

REACTION
BOILER STRUCTURE
GAS
CBC
COAL
COAL
COAL FEED
COAL SIZE
SORBENT
MATERIAL
PARTICLE SIZE
AIR
REACTION
COMBUSTION
NOx SOx
ASH RECYCLE
REACTION
COLLECTING PERFORMANCE
E.P
BAG-FILTER
GRANULAR BED-FILTER
WASTE
EROSION
LOAD CONTROL
SLUMPING BED
BED LEVEL
BED TEMP.
START-UP
USED SOLID HANDLING

FIG. 10 DEVELOPMENT AREAS OF FBC BOILER

TABLE 4. TEST FOR MAIN BED CELL (MBC)

Test item	Operation item	Variation	Remarks
i) Demonstration of low pollution level	Total air ratio	1.5 ∿ 1.25	
	Bed temperature	770 ∿ 900°C	
	Heigh of fuidized bed	1.2 ∿ 1.6 m (overflow pipe)	
	Eluidizing medium	Limestone	Synthetic desulfurizing reagent will also be used.
	Desulfurizing reagent	Limestone	Synthetic desulfurizing reagent will also be used.
	Grain size of coal	-4 mm ∿ -12 mm	
	Grain size of desulfurizing agent	Fine grain ∿ -4 mm	
	Ca/S mol ratio	Not more than 5	
	Air ratio in bed	0.85 ∿ 1.25	Air ratio in bed $= \frac{\text{air q'ty in bed}}{\text{theoretical air q'ty}}$
	Cyclone dust recycle	Recycle q'ty	
	Heat release rate	$1.5 \sim 2.7 \times 10^5$ Kcal/m^{2}h	
	Height of free board	4 ∿ 8 m	
	Coal feeding method	Pneumatic conveyor and spreader, parallel operation	
	Position of two stage combustion air supply	2.0 ∿ 6.0 m	(from bed surface)

Test Item	Operation item	Variation	Remarks
ii) Demonstration of boiler controllability			
1) Start-up	° Bed heating system	Hot air generator, overbed burner	
	° Start-up mode	Cold, warm and hot	
	° Start-up operation		
	° Start-up operation	Heat quantity charging rate, etc.	
2) Shut-down	° Shut-down method	Normal, emergency	
	° Shut-down operation	Cooling rate, etc.	
3) Load characteristics	° Bed operating conditions	Bed height, bed temperature, number of operating beds	
4) Dynamic characteristics	° Input	Sudden change in steam flow Sudden change in feedwater q'ty Sudden change in fuel consumption Sudden change in air q'ty	
5) Control characteristics	° Load change ratio and bed operation conditions	Steam flow Water feed q'ty	
	° Load change ratio and load change amplitude	Fuel consumption Air q'ty Bed temperature and bed height Number of operating beds	
iii) Demonstration of boiler reliability			
1) Wear of heat pipes in bed	Material	Carbon steel Low alloy steel Stainless steel	° Installation of test piece

Test Item	Operation item	Variation	Remarks
2) Durability of air distribution plate	Material and structure	Type of special steel Shape of openings	
iv) Smitable type of coal	Type of coal	Fuel ratio	max. 3
v) Demonstration of dust collection system	Type	Electrostatic type	Bag filter and granular filter will also be tested.

TABLE 5. TEST DETAILS FOR CARBON BURN-UP CELL (CBC)

Test item	Operation item	Variation	Remarks
i) Demonstration of low pollution level	Total air ratio	1.2 ∿ 1.4	
	Bed temperature	900 ∿ 1000°C	
	Height of fluidized bed	1.2 ∿ 1.6 m	
	Fluidizing medium	Silica sand	
	Air ratio in bed	0.9 ∿ 1.4	
	Two stage combustion air supply	approx. 2.0 ∿ 6.0 m	(from bed surface)
ii) Demonstration of controllability			
1) Start-up	Bed heating system	Hot air generator, overbed burner	
	Start-up mode	Cold, warm and hot	
	Start-up operation	Heat q'ty charging rate, etc.	
2) Shut-down	Shut down system	Normal, emergency	
	Shut down operation	Cooling rate, etc.	
3) Load characteristics	Bed operation conditions	Bed temperature, bed height, ash, coal supplemental combustion	

TABLE 6. TEST SCHEDULE OF 20 T/H FBC

FY	1981											
Month Demonstration item	4	5	6	7	8	9	10	11	12	1	2	3
Low pollution			low S coal ▨	▨	▨	▨		medium S coal ▨	▨			
Effect of operating conditions										medium S coal ▨		
Controllability							low S coal ▨					
Continuous operation											▨	▨

FY	1982											
Low pollution capability			▨	▨								
Two cells operation	▨	▨										
Effect of operating conditions					▨	▨	▨	▨	▨	▨		
Controllability											▨	▨

FY	1983											
Versatility of coals	▨	▨	▨	▨	▨	▨						

4. Results of tests

Outline of the results of the operation in fiscal year of 1981 are as follows.

As for the regeneration unit and the test dust collectors system, the test operation started in April, 1982.

(1) Operating results

After test operation of each equipment (Soda boiling, Flashing etc.), coal feeding started in May 1981. Properties of the test coals and limestone are shown in Table 7 and Table 8.

In December 1981, some equipment of the plant was modified. (See Table 9)

TABLE 7. PROPERTIES OF COALS

Type of coal		Ⓐ COAL	Ⓑ COAL	Ⓒ COAL
High calorific value (Kcal/kg)		6510	6640	6920
Surface moisture (%)		4.5	3.0	3.2
Proximate analysis	Moisture (%)	4.6	3.2	3.1
	Ash (%)	13.0	12.7	10.7
	Volatile matter (%)	47.0	30.3	38.8
	Fixed carbon (%)	40.0	53.8	47.5
Ultimate analysis	C (%)	67.00	70.08	72.11
	H (%)	5.98	4.53	5.13
	N (%)	0.92	1.68	1.47
	O (%)	13.03	9.98	9.56
	Combustible S (%)	0.07	0.55	0.71
	Incombustible S (%)	0.11	0.26	0.14

TABLE 8. PROPERTIES OF LIMESTONES

Item			A	B
Content	CaO	(%)	55.41	55.61
	MgO	(%)	0.27	0.19
	SiO_2	(%)	0.39	0.02
	Fe_2O_3	(%)	0.03	0.01
	Al_2O_3	(%)	0.008	0.04
	Ig.loss	(%)	43.13	43.89

TABLE 9. MODIFICATION ITEMS

NO.	ITEMS	DATE	COMMENTS
1	Adjustment of the tubes	6/81	Cut tubes in the bed
2	Adjustment of heat release rate (1)	12/81 ~ 1/82	Made for Covered Evapolator tubes and superheater tubes in the bed (2.0×10^6 Kcal/m^2h → 1.7×10^6 Kcal/m^2h)
3	Wind box		Divided the wind box for slumping test (3 sections)
4	Coal feed nozzle		New type nozzles were installed
5	Adjustment of heat release rate (2)	2/82	Made cover for water wall tubes and superheater tubes. (1.7×10^6 Kcal/m^2h → 1.4×10^6 Kcal/m^2h

(2) Operation data

1) Operating characteristics

Since the coal feed started in May 1981, operating hours has accumulated to 2300 hours (including 260 hours continuous operation) in fiscal year of 1981. The boiler was commissioned very smoothly. Table 10 shows an example of operating data.

TABLE 10. EXAMPLE OF TEST OPERATING DATA

Item		Unit	Ⓐ Coal	Ⓑ Coal	Ⓒ Coal
Evaporation		t/h	17.46	12.93	16.2
Main steam pressure		atg	60.1	59.8	59.9
Main steam temperature		°C	535	540	540
Feedwater flow		t/h	15.4	11.44	14.88
Feedwater temperature		°C	133	134	134
Ambient temperature		°C	22	9	11
A/H outlet exhaust gas temperature		°C	155	122	134
Total air flow		Nm^3/h	19068	17928	14456
primary combustion air flow		Nm^3/h	16068	16968	13116
secondary combustion air flow		Nm^3/h	3000	960	1340
Heat release rate		$\frac{Kcal}{m^2h}$	$2.0x10^6$	$1.4x10^6$	$1.7x10^6$
Superficial velocity		m/s	2.16	1.52	1.88
Bed temperature		°C	835	829	823
Exhaust gas characteristics	O_2	%	3.49	3.44	3.51
	NOx	ppm	61	223	238
	SO_2	ppm	10	27	33

2) Start-up and shut-down

Figs. 11 and 12 show the test results of a cold start and a hot start.

The full evaporation was reached in four hour on cold start-up, and on hot start-up in two and half hours.

It can be concluded that the limiting factor of the start-up time is the drum stresses due to the difference in temperature as is the care for the conventional boiler unit.

When shut-down the boiler, it takes about twenty minutes from coal feed closed to air flow shut off.

We have no experience of clinker formation during the operation up to now.

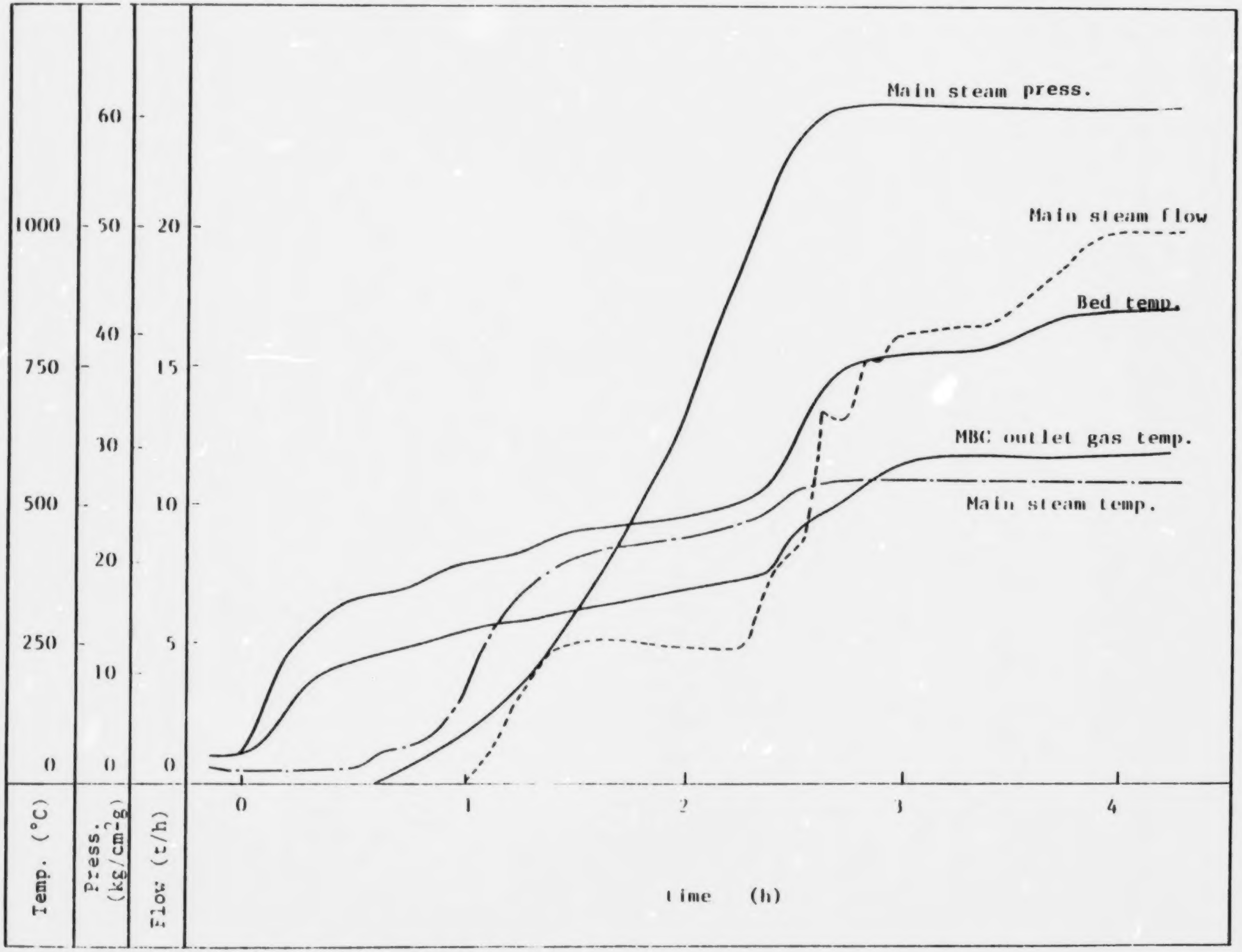


FIG. 11 RESULT OF BOILER START-UP (COLD START)

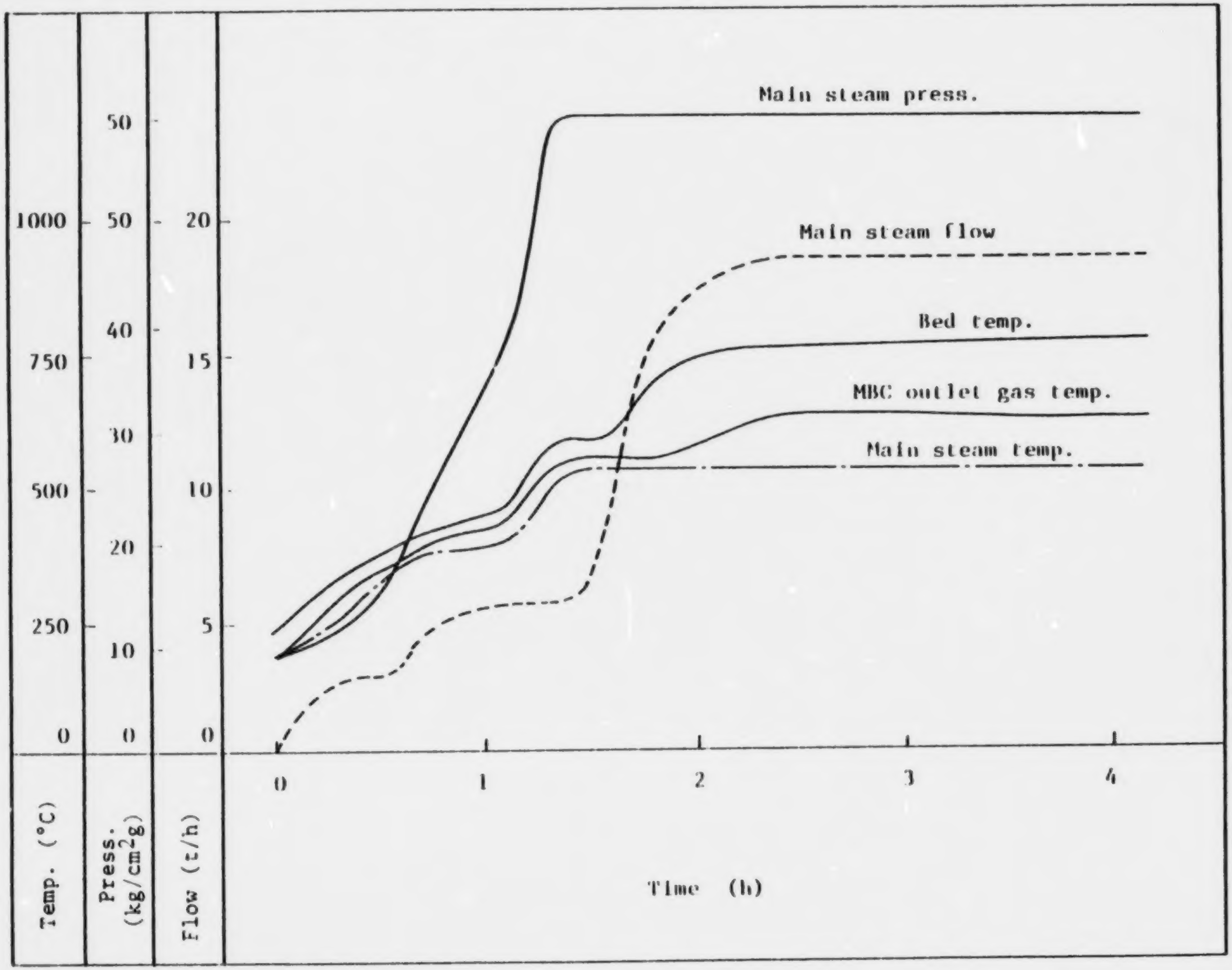


FIG. 12 RESULT OF BOILER START-UP (HOT START)

(3) Low pollution characteristics

1) NOx

Test results with the use of B coal are shown in Figure 13. Effect of two-stage combustion on NOx is remarkable; i.e. by lowering the bed air coal ratio from 1.0 to 0.91, NOx is reduced by 135 ppm from 220 ppm to 85 ppm. Incidentally, A coal of low N content gave the NOx value of 60 ppm at the bed air coal ratio of 0.89.

2) SOx

Change of desulfurization efficiency with bed air ratio is shown also in Figure 13. Desulfurization efficiency was 95% at the bed air coal ratio of 1.01. Even at the bed air coal ratio of 0.91, the condition of reducing NOx, and desulfurization efficiency of 91% was still retained.

(4) Reliability of equipment

Reliability of boiler equipment is shown in Table 11.

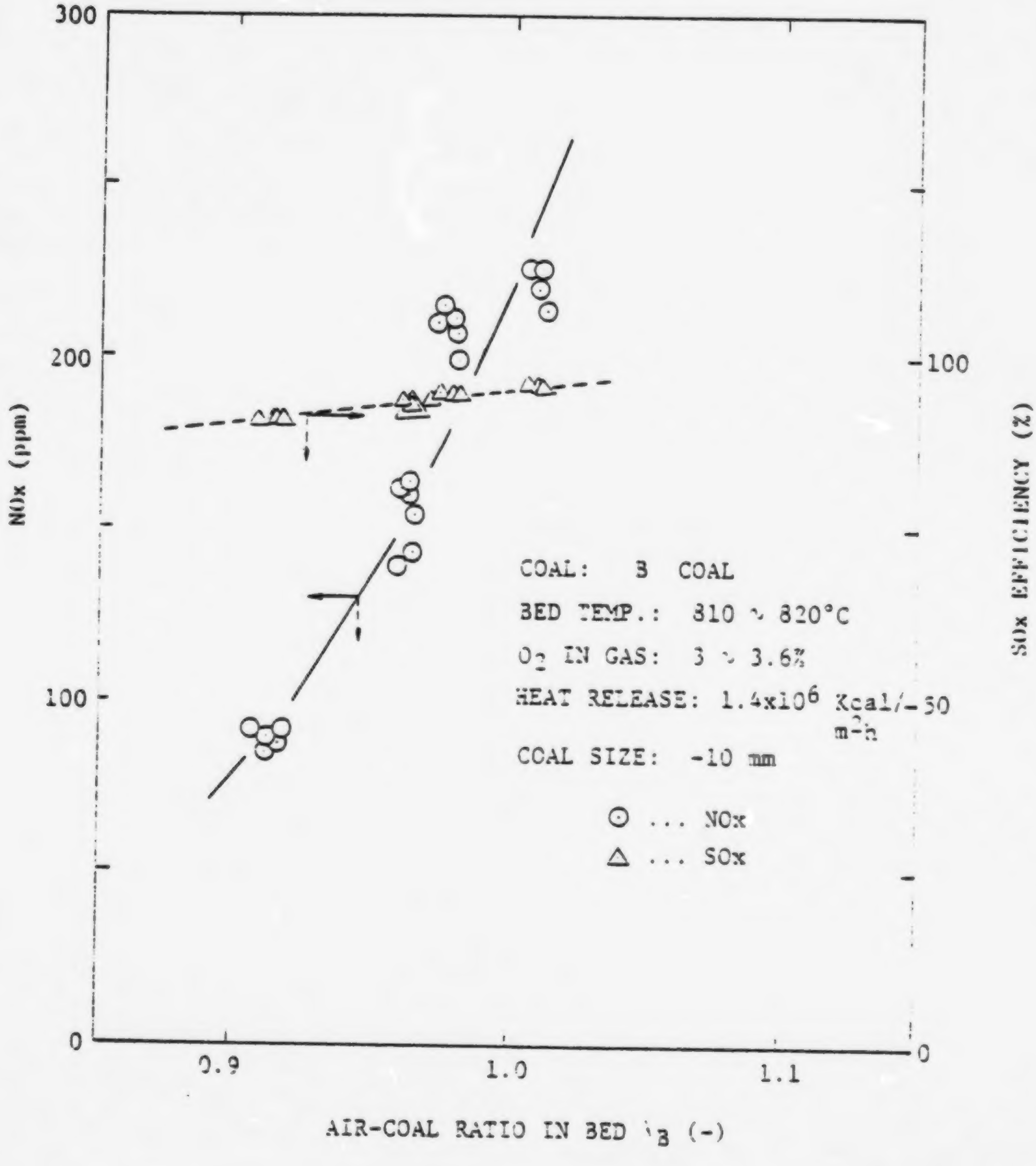


FIG. 13. AIR-COAL RATIO IN BED, NOx, SOx

TABLE 11. RELIABILITY OF BOILER EQUIPMENT

No.	Equipment	Description
1	Heat transfer tubes in the bed zone	Heat transfer tubes consisting of a part of evaporator primary superheater and secondary superheater were found to be having higher heat transfer coefficient than expected, and thus excellent heat transfer performance of the FBC boiler was confirmed. Corrosion and erosion of heat transfer tubes has been checked at regular intervals, but inspection will be continued as operating hours is still not long enough to make any conclusion.
2	Heat transfer tubes in the free board and convection zone	A small amount of fly-ash has deposited on the upper surface of horizontal heat transfer tubes of evaporator and economizer installed in the rear section of flue gas pass, but it was found easy to remove them only by slight air blowing operation.
3	Air distributor (including bubble-caps)	No deforming and no corrosion and erosion were detected as to the air distributor.
4	Coal feed nozzles	The inspections carried out several times by drain off the bed medium during plant shutdown revealed no corrosion and erosion nor plugging.
5	Bed medium drain-off pipe	Flidization of bed medium was in good conditions, no symptom of worsening in fluidization was sighted, and also no slightest formation of bulk and clinker was observed.

5. Summary

Test operation is in progress without any appreciable discrepancies against the original scheme though test operation results of this year revealed some unpredictable facts such as higher heat transfer coefficient in the fluidized bed than what was obtained by the bench scale study. Corellation between the test data and the bench scale data could also be established which would serve as the basis of a scale-up. As for the reliability of equipment, however, it is deemed necessary to perform long-term test for the purpose of verification. In the test operation planned in 1982, it is aimed at raising the reliability of the FBC plant in wider areas including a spent sorbent regeneration unit and experimental dust collectors.

III. Future prospect

1. Problems to be overcome for commercialization

As explained, development of the FBC boiler is in the stage of test operation on the pilot plant scale. Therefore many problems lie ahead to be solved before the FBC power plant can be commercialized which should be competitive with the conventional pulverized coal-fired boiler plus flue gas treating units, the technology of which are already established. Possible areas to be solved are shown below item wise. Regardless of itemization, however, each item is correlated with the other.

(1) Clarification of the most suitable coal species

The commercialization of the FBC boiler will be realized in very short term, if it is aimed, at the target in the immediate future i.e., at becoming competitive with pulverized coal-fired boiler in special type of coal, rather than to seek to compete with it in such coal varieties as are generally accepted by the pulverized coal fired boilers in Japan.

(2) Adaptation to wide specification ranges

It is desired to develop such a boiler as can satisfy as wide specifications of coal as possible so that flexibility in coal procurement can be retained.

(3) Aptitude as an middle-loaded thermal power plant

Electric power distribution in Japan is operated fundamentally according to the principle of incremental fuel costs. Therefore it is quite likely that the coal-fired thermal plant will become more alloted the middle load in the operation of the system as compared with nuclear power plants. In this sense, the FBC boiler power plant has, as one of the coal-fired unit, much to be checked and improved, for instance, partial load operation characteristics, response to load variation, and start-up/shut-down performances.

(4) Development of ash disposal system

It is indeed a common case that ash disposal encounters the difficulty in reality in the operation of the actual coal-fired power plant in Japan. Furthermore, because of the addition of lime stone, the ash from the FBC boiler is much greater in amount than that of pulverized coal-fired boiler, and in terms of quality, rich in Ca content and of unmolten type. For this reason there are a lot of things to be checked and developed in connection with clarification of basic properties of ash, measures for pollution prevention and means of ash utilization.

(5) Verification of anti-pollution performance

In the operation of the FBC boiler, such operation conditions as coal specifications, excess air and Ca/S ratio give the combined effects upon SOx and NOx in flue gas as well as upon combustion efficiency. It is therefore necessary to establish what will become of these combined effect in the operation of the commercial-scale plant.

(6) Clarification of the equipment reliability

Corrosion and errosion of the heat transfer tubes in the bed zone must be checked in great care, and measures must be worked out if necessary.

(7) Clarification of the overall economy

The FBC boiler has many excellent advantages including adaptability to wider coal varieties, lower-pollution performances, and high heat transfer coefficient. But, whatever the superiority of the FBC boiler may be to the pulverized coal-fired boiler in each of the aspects, its commercialization by daring the risk of adopting new technologies will not become possible unless it is competitive enough from the viewpoint of the plant as a whole.

Therefore it will be necessary to clarify overall economy of the FBC boiler power plant through optimization of the plant system including flue gas treatment units, establishment of ash recycling subsystem including carbon burning cell for improvement of combustion efficiency, etc.

As mentioned above, a lot of problems lie to be solved along the way to the commercialization of the FBC boiler. In view of this, EPDC is now studying the construction of a demonstration plant as the next step to pilot plant.

2. Closing Remark.

The efforts of developing the FBC boiler in Japan is like a horse race in which it is running after the preceding horse, i.e. the pulverized coal-fired boiler backed by the cheers of "nation-wide significance resting on the widening of usable coal varieties". Whether it can come up with its forerunner and realize the competitive commercial plant depends greatly upon the development ahead of the world's energy situation. We believe it will become a reality.

CLEAN COMBUSTION OF PETROLEUM COKE IN A PYROFLOW™ CIRCULATING FBC

by

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and

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presented at
The Canadian Institute of Energy
AFBC Symposium
Calgary, Alberta, Canada
May 27, 1982

INTRODUCTION

Petroleum coke has a very high specific energy content. Use of high sulfur petroleum coke as a fuel source in North America has been limited, however, because of environmental restrictions. Some high sulfur coke finds demand in the cement industry, in which limestone is an ingredient in the process. Other high sulfur coke finds itself in the export market to Europe or the Far East, where environmental regulation permits high sulfur fuel burning or where petroleum coke is blended with other low sulfur, low-grade fuels. Most of it has been stockpiled or buried as waste. As world supplies of light and sweet crude oil dwindle, more sour crude will be processed, resulting in the production of an even larger amount of high sulfur petroleum coke byproduct.

The PYROFLOW™ circulating fluidized bed combustion (CFBC) system offers an economic and environmentally acceptable method of burning this fuel, which will be used principally for power and process steam production in refinery and petrochemical plants.

The PYROFLOW system is offered in North America by Pyropower Corporation, owned by General Atomic Company of San Diego, California, and Ahlstrom Company of Finland.

The CFBC system burns petroleum coke efficiently and cleanly meeting the following requirements:

- Removes sulfur dioxide during or after combustion. (Sulfur content in petroleum coke can reach as high as 9%.)
- Burns a low volatile coke with sufficient combustion efficiency.

- Reduces or prevents the formation of NO_x due to oxidation of fuel nitrogen in the coke. (Fuel nitrogen in petroleum coke can reach 2 to 2.5%.)

- Feeds and burns coke fines, such as coke breeze from fluid coking, or carbon fines generated from the combustion of delayed coke.

- Prevents fireside corrosion due to high concentration of corrosive metals such as vanadium, nickel, and sodium.

SYSTEM DESIGN

The system (as shown in Fig. 1) consists of a combustion chamber where the bed material, including the fuel, is fluidized with high-velocity air, which turbulently transports the solids up the full height of the combustion chamber. Combustion of the fuel takes place as it rises, and heat is transferred to the membrane water-wall tubing that forms the walls of the combustion chamber. The hot combustion gases with the entrained solids exit at the top of the combustion chamber into the hot cyclone. The cyclone separates the solids from the combustion gases and returns the solids, including any unburned solid fuel, through a nonmechanical seal to the combustion chamber where they mix with incoming fresh fuel. The long solids residence time at combustion temperature and the retention and continuous recirculation of the solids ensure high combustion efficiencies for a wide range of fuels, including coke fines, and result in an ideal system for the mixture of fine limestone with the fuel for efficient SO_2 retention in solid ash form. Because fine limestone with high total surface area can be used in the CFBC, calcium utilization is substantially higher than that in the bubbling FBC.

The lower section of the combustion chamber includes an air distribution grid and a bottom ash removal system. The chamber is surrounded by a membrane wall using 63.5 mm (2-1/2 in.) diameter tubes on 76.2-mm (3-in.) centers. Approximately 40% to 50% of the heat generated is transferred to

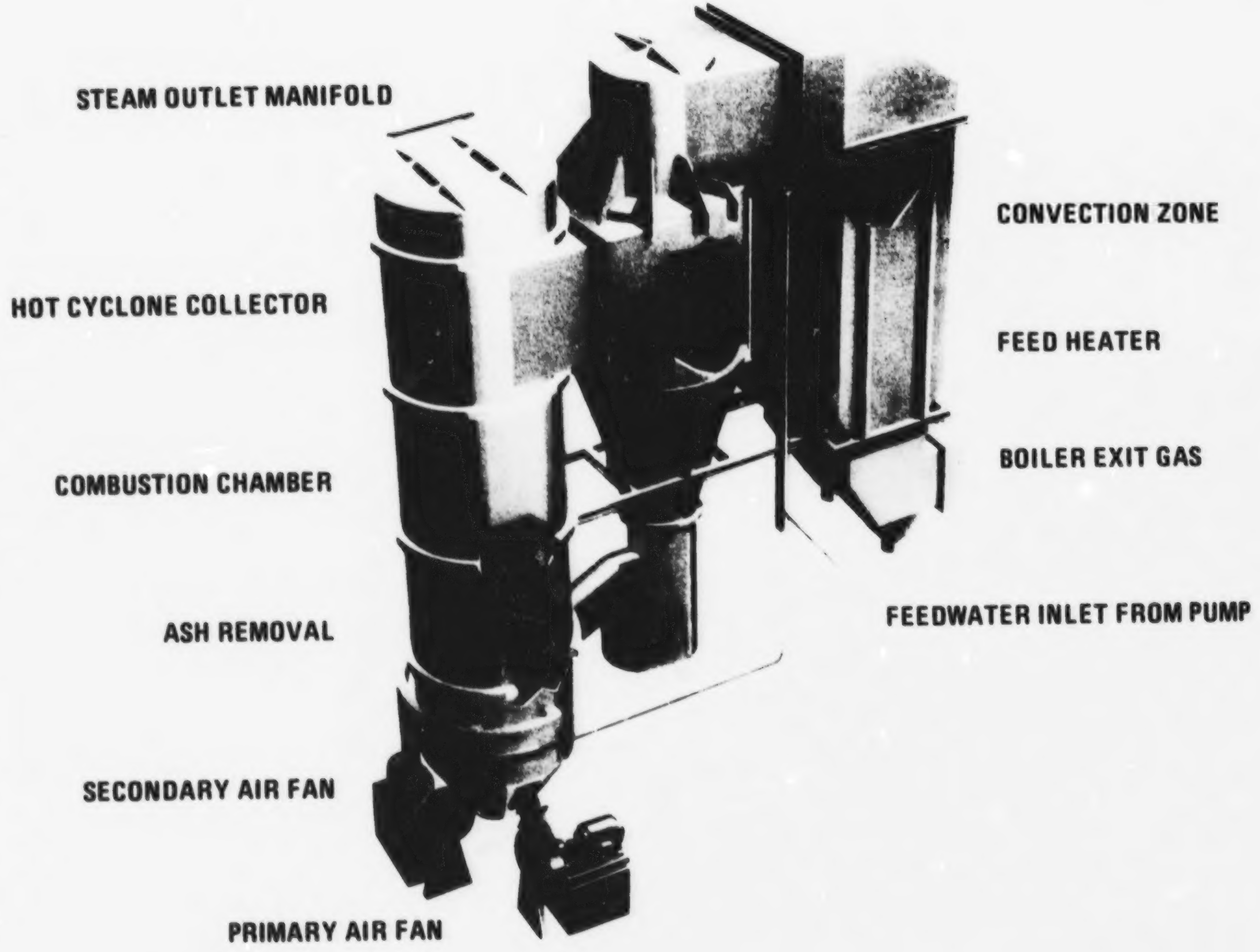

STEAM OUTLET MANIFOLD
HOT CYCLONE COLLECTOR
COMBUSTION CHAMBER
ASH REMOVAL
SECONDARY AIR FAN
PRIMARY AIR FAN
CONVECTION ZONE
FEED HEATER
BOILER EXIT GAS
FEEDWATER INLET FROM PUMP

Fig. 1. Pyroflow circulating fluidized bed combustion system

the water walls in the combustion chamber at full load. The circulating solids ensure that heat transfer coefficients to the membrane wall tubing are typical of fluidized bed heat transfer values. There are no heat transfer tubes perpendicular to the flow of solids. In regions where the flow changes direction, heat transfer tubing is protected with abrasion-resistant refractory.

During more than 3 years of operation of the first commercial CFBC plant at Pihlava in Finland (Ref. 1), there have been no boiler tube or refractory failures, which demonstrates the validity of the design philosophy.

Provisions are made for primary and secondary air supply to the combustion chamber. The primary air is supplied to the wind box below the fluidizing grid and provides the initial fluidization air flow. The secondary air provides a staged combustion effect to ensure high combustion efficiencies and to minimize NO_x production.

The hot combustion gases with fly ash that exhaust from the cyclone flow to a convective heat transfer section containing superheat, evaporative, and economizer tubing. This part of the boiler is typical of any solid fuel boiler and includes soot-blowing and ash-removal features.

The high velocities in the combustion chamber also permit reductions to about 25% of full load without bed slumping. Continuous load following with rate changes of 5% to 10% per minute is also possible. On the smaller 6.25-kg/s (50,000-lb/hr) Pihlava system, load reductions of 50% in 3 minutes have been demonstrated.

FIRESIDE CORROSION PREVENTION IN FBC

Boilers burning petroleum cokes containing high concentration of vanadium, nickel, and sodium are susceptible to high temperature and low temperature fireside corrosion. High temperature corrosion of the superheater and reheater is due to the deposit of low temperature melting eutectics of vanadium complexes, e.g., $Na_2O \cdot V_2O_5$ (melting point, 1050°F). Low temperature corrosion of the air preheater and dust collector is due to vanadium and nickel catalytic oxidation of SO_2 to SO_3. However, the magnesium oxide and calcium oxide present in the limestone or dolomite used in a FBC is the best inhibitor of vanadium-type corrosion.

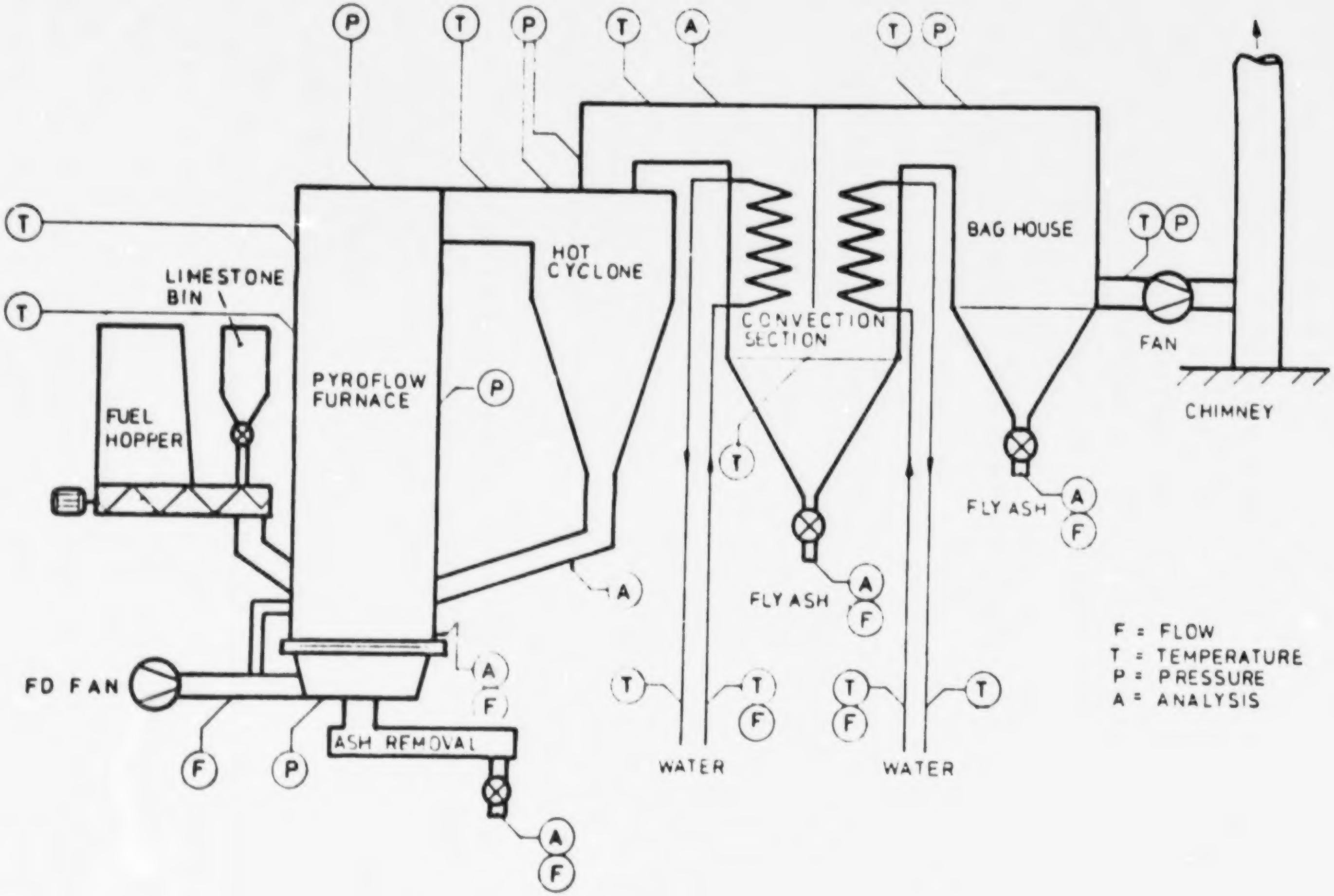
Magnesium oxide in the limestone or dolomite will contribute to the forming of high melting point vanadium compounds such as V_2O_5-MgO (Refs. 2-5). This complex scavenges the low temperature melting V_2O_5 and poisons the catalytic effect of V_2O_5 in the conversion of SO_2 to SO_3. The presence of CaO in the combustion chamber reduces the availability of SO_2 for oxidation to SO_3 thus inhibiting corrosion.

The lower combustion temperature of 1550° to 1650°F in the CFBC further reduce the possibility of high temperature corrosion such as that induced by molten ash.

PYROFLOW™ PILOT FACILITY

Both fluid coke and delayed coke combustion were tested in the PYROFLOW™ pilot facility in Finland as part of an on-going test program to demonstrate performance requirements for North American customers. The pilot CFBC used in the tests has a 0.8 m (32 in.) diameter combustor (see Fig. 2). It is 6 m (20 ft) in height. Combustor temperature is controlled by bayonet cooling tubes hanging from the top of reactor. The length of the tubes inside the furnace is adjustable. Flue gas from the cyclone is cooled in a boiler bank before entering the baghouse, and there is a venturi scrubber on line after the baghouse. If necessary, the baghouse may be bypassed.

There is also an option for recirculation of a given amount of fly ash from the baghouse back to the reactor.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WATER
WATER
F = FLOW
T = TEMPERATURE
P = PRESSURE
A = ANALYSIS

Fig. 2. Pyroflow pilot plant

The continuous off gas analyzing equipment on line after the cyclone is as follows:

NO/NO_x	Beckman, Model 951
SO_2	Hartman & Braun, Uras 7 N
CO	Hartman & Braun, Uras 7 N
O_2 (in dry gas)	Taylor Servomex, Type OA 272
O_2 (in wet gas)	Westinghouse, Model 218

SYNCRUDE FLUID COKE COMBUSTION

Syncrude coke is a byproduct produced in large quantities by the Syncrude Canada Ltd. oil sands extraction plant at Fort McMurray, Alberta, Canada. It has high specific energy content, being high in carbon content and low in ash. It has been difficult to use as fuel because it is low in volatile matters and high in sulfur. Carbon in the coke is graphitic or other relatively inert carbon forms. Table 1 gives the analysis of the fluid coke. The sulfur content averages 6.5% for the test series but can range as high as 9%. The particle size of the Syncrude coke is 2 mm x 0, with a mean size of 0.15 mm.

According to the emission guidelines of the Canadian Ministery of the Environment, Syncrude coke belongs to the group of solid fuels in which uncontrolled SO_2-emission is over 2.58 g SO_2/MJ_{HHV} (6 lb/MMBTU). Thus, a minimum of 90% SO_2 removal is required. NO_x-emission must not exceed 0.258 g NO_2/MJ_{HHV} (0.6 lb/MMBTU).

In 1981 CANMET, Canada Centre for Mineral and Energy Technology, sponsored a Syncrude coke test program in the 0.8 m pilot facility in the Hans Ahlstrom Laboratory, Karhula, Finland. The most important objectives of the test runs were to find the optimum run conditions in which the best combustion efficiency and minimum pollutant emissions could be achieved. Limestone was used to control SO_2-emission, and the effects of different input variables to minimize limestone consumption were examined.

TABLE 1
SYNCRUDE FLUID COKE
Chemical Composition

Moisture %	2.6
Volatile %	5.4
Vanadium	2500 ppm
Nickel	800 ppm
Ultimate analysis (dry)	Wt%
Carbon	81.7
Hydrogen	1.8
Nitrogen	1.5
Sulfur	6.6
Ash	6.6
Oxygen	1.8
HHV (dry)	13500 Btu/lb

TABLE 2
SYNCRUDE
FLUID COKE COMBUSTION TEST
Operating Conditions

Coke size	2 mm X 0 (150 micron mean)
Limestone size (mean)	75-90 micron (Gotland)
Combustion temperature	1550-1650 °F
Excess Air	12-31%

TABLE 3
SYNCRUDE FLUID COKE
Performance

SO_2 Retention	90-93.7%
Ca/S Molar Ratio	1.7-2.1
NOx (EPA limit 0.6 lb/MMbtu)	0.26-0.4 lb/MMBtu (170-270 ppm)
CO	57-470 ppm
Combustion Efficiency	97-99%

Eighteen tons of Syncrude coke were burned in the pilot plant. Gotland limestone was used to capture SO_2 as $CaSO_4$. The mean particle size was about 90 micron. The operating conditions for the test are given in Table 2, and the overall performance of the test series is summarized in Table 3.

The Syncrude coke combustion tests led to the following results and conclusions:

- With Gotland limestone, 90% sulfur retention was achieved with a Ca/S ratio of less than 2. With baghouse flyash reinjection, the Ca/S can be improved slightly to 1.7 for the same retention level.

- Combustion efficiencies were 97% to 99% and were a strong function of combustion temperature. The best efficiency was attained at around 900°C (1650°F), with reasonable sulfur capture. The increase of secondary air or excess air also improved combustion efficiency. Baghouse flyash recirculation did not produce much improvement.

- NO_x emission varied between 0.26 to 0.4 lb/MMBTU (170 ppm to 270 ppm). Despite higher combustion temperature, lower NO_x was obtained with increasing secondary air, i.e., stronger staging of combustion.

- Carbon monoxide varied from 57 to 470 ppm. Simultaneous reduction of CO (57 ppm) and NO_x (186 ppm) were attained at 5.7% O_2 in one test, which was designed to demonstrate stringent emission standards in some parts of California.

DELAYED PETROLEUM COKE

Delayed cokes usually have higher volatile matters than fluid coke and are available with much larger particle size and less fines. Tables 4 and 5

TABLE 4

DELAYED PETROLEUM COKE
Chemical Composition

Moisture	%	6.4
Volatiles	%	12.7
Ultimate analysis (dry)		Wt%
Carbon		89.8
Hydrogen		4.16
Nitrogen		1.24
Sulfur		3.67
Ash		0.50
HHV (dry)	Btu/lb	15590

TABLE 5

DELAYED PETROLEUM COKE
Combustion Results

OPERATING CONDITIONS	
Coke size	3/4" × 0
Limestone Size (average)	170 μm
Excess Air	10-31%
Combustion Temperature	1545-1685 °F
PERFORMANCE	
SO_2 Retention	90-94%
Ca/S Molar Ratio	1.8-2.4
NO_x	60-250ppm
CO	50-450ppm
Combustion Efficiency	95-98%

TABLE 6

HEAVY BITUMEN OIL CHARACTERISTICS

	Wt%
C	83.6
H	9.78
S	4.88
ASH	0.06
HHV	18,100 Btu/lb (dry)
V	174 ppm
Ni	58 ppm
Viscosity	795 centi strokes (at 270°F)
Softening point	over 140°F
Sp. gr (at 77°F)	1.036

present the coke characteristics and test results of a Gulf Coast refinery delayed coke. A 3/4 in. x 0 delayed coke was used. Combustion temperature was about 900°C (1650°F). Results similar to those for Syncrude coke were obtained.

RESIDUAL OILS COMBUSTION

For a refinery that does not have a coking unit to further upgrade the residual oils, the PYROFLOW™ CFBC can accept the high sulfur residue as fuel if the residue is pumpable. Tables 6 and 7 show the heavy bitumen (residual) oil characteristics and the PYROFLOW™ combustion performance in the pilot plant. Due to the potentially oily flue dust associated with oil combustion, an electrostatic precipitator may be used instead of a baghouse.

Other low BTU fuel gases in a refinery, such as sulfur tail gas or CO gas streams, can be routed to the CFBC for heat recovery and sulfur cleanup.

COMMERCIAL SCALE PYROFLOW™ UNITS

The successful operation of the early CFBC systems has lead to the acceptance of this advanced circulating fluidized bed technology in Europe, Scandinavia, and the U.S. These systems make an economically and environmentally attractive replacement for oil-fired process steam and cogeneration systems in the complete spectrum of industrial requirements.

By the end of 1981, six commercial CFBC units were in operation and six were under construction (Table 8), including one in the U.S. at Bakersfield, California, for Gulf Oil Exploration and Production. This first unit in the U.S., which is scheduled for startup in late 1982, will generate steam for heavy oil recovery by burning coal. It must meet stringent emission standards.

TABLE 7
HEAVY BITUMEN OIL
Performance

SO_2 Retention	85-90%
Ca/S	2.2
NO_X	113 ppm (0.164 #/MMBtu)
CO	50 ppm
O_2	3.75%
Combustion Efficiency	99.8% +

TABLE 8
CIRCULATING FLUID BED COMBUSTOR INSTALLATION LIST

Customer	Startup	Fuel	Output	Steam Conditions	Application
Pihlava Board Mill, Finland	1979	Peat, wood, and coal	5.6 kg/s (45,000 lb/hr)	8.5 MPa (1230 psig); 521°C (970°F)	Cogeneration
Suonenjoki, Finland	1979	Peat, wood, and coal	7 MW(t) (22 10^6Btu/hr)	1.1 MPa (160 psig); 121°C (250°F) hot water	District heating
Kemira Oy, Finland	1980	—	—	—	Sludge incineration
Kauttua, Finland	1981	Peat, wood, and coal	25 kg/s (200,000 lb/hr)	8.5 MPa (1235 psig); 499°C (930°F)	Cogeneration
Hyvinkaa, Finland	1981	Coal, peat, and oil	25 MW(t) (85 10^6Btu/hr)	1.1 MPa (160 psig); 168°C (335°F) hot water	District heating
Skelleftea, Sweden	1981	Peat, wood, and coal	7 MW(t) (22 10^6Btu/hr)	1.1 MPa (160 psig); (179°C) 355°F hot water	District heating
Ruzomberok, Czechoslovakia	1981	—	—	—	Sludge incineration
Hylte Bruk, Sweden	1982	Peat and coal	17.9 kg/s (143,000 lb/hr)	6.6 MPa (960 psig); 449°C (840°F)	Cogeneration
Gulf Oil Exploration, USA	1982	Coal	6.3 kg/s (50,000 lb/hr)	17.2 MPa (2500 psig); 354°C (670°F)	Enhanced oil recovery
Koskenkorva Distillery, Finland	1983	Peat and oil	6.9 kg/s (55,000 lb/hr)	4.2 MPa (610 psig); 499°C (840°F)	Process steam
Kemira Chemical; Finland	1983	Peat and oil	19.4 kg/s (155,000 lb/hr)	9.0 MPa (1305 psig); 516°C (960°F)	Cogeneration
Austria	1984	Lignite and wood waste	18.8 kg/s (150,000 lb/hr)	8.5 MPa (1235 psig); 499°C (930°F)	Cogeneration

The fourth and largest of the CFBC systems started operation at Kauttua, Finland, May 1981 (Ref. 6). The 65 MW(t) (200,000 lb/hr) CFBC boiler has demonstrated 100% load for cogeneration at 1200 psig and 900°F on mixed fuel of coal, peat, and wood waste. To demonstrate this large-scale CFBC system's ability to meet U.S. emission standards, a program was initiated to burn 2-1/2% sulfur coal with limestone addition for SO_2 capture. Combustion efficiencies over 98% were consistently obtained, and emissions were a fraction of those specified by EPA standards. Load response of 5% to 10% per minute was demonstrated. The electrostatic precipitator appeared to be about 99% efficient. Substances of environmental concern, such as CFBC residues, polynuclear aromatic compounds, and trace elements, were analyzed.

The successful operation of Kauttua and its demonstrated reliability have led to design and development of larger systems. At this time unit sizes of up to 50 kg/s (400,000 lb/hr) of steam capable of generating up to 50 MW(e) are commercially available for burning a wide range of fuels. Increasing interest by the utility and process industries will be addressed this year with the development of a 100-kg/s (800,000-lb/hr) unit capable of generating about 100 MW(e).

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DISCUSSION

First Speaker - Frank Friedrich (CANMET)

1. Q. R.A.S. Brown (Chinook Fuel Innovations Ltd.)
Is the turn down of 4-1/2 overall or per unit?

A. Frank Friedrich
Per Boiler.

Q. R.A.S. Brown
Secondly, as you have ash reinjection, I take it you are not using a separate carbon burn-up cell?

A. Frank Friedrich
That's right; there is no carbon burn-up cell.

2. Q. John Rawlings (Esso Resources)
Could you comment on their material program?

A. Frank Friedrich
Well first of all we do have one and this is something we are doing in conjunction with Nova Scotia Power Commission. We are planning a research program involving a 10,000 hr combustion test in a pilot scale unit to investigate corrosion of suitable boiler materials for fluid bed applications.

Q. Blake Forest (Esso Resources)
I understand that there is a consideration being made to using the bottoms of the CANMET process for the Summerside pilot project. Is there any research done in this part of the field to date?

A. Frank Friedrich
None has been done, there has been about a five minute discussion on the possibility.

Second Speaker - Ken Smith (Dorr-Oliver)

Q. David Osborne (Simon Carves)
One of the most interesting aspects of this type of installation which wasn't referred to at all is the cost of the installation itself, it's operating cost and in particular the capital cost. I wonder whether you would care to add any comments with regards to the costs?

A. Ken Smith
I'm afraid the comments in that regard are rather hard to generalize on.

Q. David Osborne
Perhaps you could refer to the Coal Valley experience?

A. Ken Smith
All right. With respect to that particular plant we did not get involved in the capital cost evaluation of the total project. Our participation was mainly in the fluidized bed combustor itself; equipment on basically a mechanically erected basis, but building and electrical and services and so on by others. For 253 million BTU's per hour though we are looking at a combustion system; 3 stages of cyclones; ducting heat exchangers; blowers and a control system supply in the area of 10 to 10-1/2 million dollars.

I think you can safely double that to come to the finally installed system and I think the conclusion by Luscar on this particular study was that the capital cost could not be justified for the savings in coal at this time. I guess that is really a function of the cost of coal. Certainly there is an effect of the operating horsepower. I do not remember the horsepower in running that particular combustor. Certainly one of the major factors in the capital cost for example was the equipment configuration. The need in this particular study to utilize reasonably good gas clean up. There were tremendous amounts of dollars tied up just in those cyclones, the duct work associated with them and the structure to hold them. So I think that colours the system quite a bit. I think capital wise the system will come down considerably looking at the indirect use, for indirect capture energy for a dryer via a heat exchanger.

Comments by Frank Friedrich (CANMET)

If I may add a word on the economics, it is going to be quite site specific and I would suggest that in the Luscar situation where the capital cost had to be amortized by the savings of clean coal, which was the normal dryer fuel, it doesn't look so good, but if the dryer fuel is natural gas it could be very interesting.

Q. Frank Friedrich
I'd like to ask a question to Ken Smith regarding the Shamokan unit. How many hours of operation do you have on that unit now?

A. Ken Smith
The last report I have Frank is to the end of March this year and we had about 2400 hours. The longest continuous run on culm itself within that 2400 hours was 910 and 920 hours. That's with culm; culm only; culm and limestone;

in that limestone is not necessarily continuous feed or culm plus some soft coal which is used in the initial heat up stages. The culm itself is not sufficiently high in heat release to offset the very high front end load of the water walls and in initial heat ups the higher grade coal is used and gradually phased out in favour of culm.

Q. Ron Brown (Chinook Fuel Innovations Ltd.)
What has the experience been with the Shamokan material? Have there been problems in disposal?

A. Ken Smith
On disposal and on physical handling there have been no problems at all. The only time that any particular problem of handling was found was when the feed size was allowed to get a little bit on the coarse side, and we started to sand out in the ash cooler itself, although there was provision made in the bottom of that ash cooler for bottom discharge of trapped material and therefore we had the escape valve already built in. It was found that in the fluidized bed itself, the combustor was less sensitive to the oversize feed material but I guess we are a little tighter on our space rate designs in the cooler itself. Aside from that, size distribution wandering beyond plant design, there have been no problems in handling the material as designed.

Q. Ron Brown
How is it disposed of?

A. Ken Smith
It's hauled back to a dump.

Third Speaker - Arnold Manaker (TVA)

Q. David Osborne
How many hours do you have on the unit?

A. Arnold Manaker
We probably have about 60-70 hours on the unit, total ups. So really we are just checking the unit out right now.

Q. David Osborne
Can you comment on the types of coals?

A. Arnold Manaker
The primary design for that unit is Kentucky No. 9 which is a high sulphur bitumunous coal. We will probably use that coal for the first 3 years of the test programs. We are going to be probably testing Texas lignites and some bitumunous coal from the west, as well as possibly some coal wash tailings.

Q. David Osborne
Are there problems with lignite because of the extra moisture?

A. Arnold Manaker
I think we will have to take a look at that but we do have the dryer before it goes into the fluid bed and we can simply dry them.

Q. David Osborne
Will it dry the whole range of coals?

A. Arnold Manaker
I think we are going to have to just take a look when we get there. We do have the dryer facility if we have to.

Fourth Speaker - John Stringer (EPRI)

Q. Richard Herd
When are these problems going to be overcome?

A. John Stringer
The developments over the last few years have been really extremely optimistic in fact. A few years ago just after these corrosion events had started to appear for example, it looked as if we were in real trouble. We now believe that for steam raising so long as we are careful, we now know enough, and we have some tools available to use like the solid state stabilized zirconia electrolytic oxygen probe for example. We think, we are not sure, but the TVA experiment will show us this but we're really fairly optimistic. We're not so optimistic about air heating, but in steam raising, I think it's alright. You'll appreciate if you're only talking about steam at something like 700°F, you don't have any of those materials problems at all. The uncooled support members in the bed, I think that's OK, so long as you watch it and again do things properly. The solids handling problems, I really don't have a good feeling about that. At one time it looks alright and then all of a sudden you discover you're in all sorts of trouble. You discover for example, and this is a specific example, you find that the coal dryer is not quite big enough in capacity so you are not quite getting it dry enough every day. Whereupon as Arnold said, the whole of your coal feed system jams and it is quite difficult at that point to unjam it. You can see how complex it is and what a lot of little pipes there are. We are I think...some people at least...are very optimistic about using spreader stokers if you can combine it with proper recycle. We think the disadvantage people saw in overbed feeding may well not be there with recycle. So long as you don't buy

yourself more problems with the recycle and recycle injection part of it, it may well be that you can get away with overbed feeding. Raymond Hoy had been saying this for years. So if the TVA experience which will be the first time we get a good, well instrumented chance to check this out, if this tells us, yes indeed we can get away with overbed feeding, then I think a lot of our problems disappear. I'm reasonably optimistic. I think that the program that Arnold described before is one which will really tell us in a fairly short period of time whether we can do it or whether the problems are major but in the main for boilers, I am quite optimistic. I may not sound so but I am.

Comments - Arnold Manaker (TVA)

The first thing that's going to be looked at in the 20 MW TVA unit is whether we can live with overbed feeding in a US utility situation and the second issue that is going to be addressed is the control issue in this test plant, say about 18 months operation to check this out.

Q. Doug Heaton (Syncrude)
We're looking into the possibilities of fluid bed combustion technology with syncrude coke. Now our coke has in excess of 1500 ppm of Vanadium. Now people tell me don't worry the limestone will mop it all up, all is well. Can you make some comments about how much we should worry about this (synopsis of question - Is vanadium a problem with syncrude coke?)

A. John Stringer
I think that's an interesting issue. In principle, that's right, you control vanadium in other systems by the addition of magnesium oxide to form magnesium vanadate which has a fairly high melting point and gives you a low activity of the V_2O_5 component so you don't normally form a fouling or corrosive deposit. Now calcium has been shown in gas turbine fuels to be able to do the same thing as magnesium but to be rather less effective. Now we have a large excess of calcium here so that on balance you would expect it to operate that way and you would think that it would probably not be a large problem.

I have to say, however, that the whole of this business is filled with people making their best guesses and being proven wrong. So one needs to check it out. There is a problem of course anytime you burn something like petroleum coke, in the low reactivity of the coke itself so that the carbon inventory in the bed goes up and that means in relation to this business of a bubbling bed where you have the emulsion phase, the emulsion phase has relatively low oxygen activity because that's where the carbon is combusting and the transfer through the emulsion phase of oxygen is slower than we thought it was going to be. The consequence is that with a low reactivity fuel you might run into slightly larger problems of low oxygen potential than the ones that we are used to. This might produce some more corrosion problems for you. However, on the good side, that reduces your chance of vanadium corrosion because in that case if you are at a sufficiently low oxygen pressure then you form V_2O_4, or VO_2 if you like, the stable oxide phase rather than V_2O_5; the VO_2 has a very high melting point and should give you no problems at all. It's rather difficult to make a specific answer, you are going to have to test it and I can suggest a test program for you. I'm not going to pay for it though!

Fifth Speaker - Akihiko Tamura (EPDC - Japan)

Q. Arnold Manaker
Are you going to be incorporating recycle or will you stay with a carbon burn-up bed?

A. Akihiko Tamura
The Wakamatsu pilot-plant has a carbon burn-up cell as you know and the ash recycling test as well as CBC operation test will be conducted separately. Did I answer your question?

Comment by Arnold Manaker

In the USA we have moved away from CBC.

Response Akihiko Tamura

Yes, I understand the situation but we have to confirm the recycling as well as the CBC operation by the Wakamatsu pilot plant. The test is now being operated.

Q. Ken Smith
How many operating hours have been logged on the plant?

A. Akihiko Tamura
We have operated something like 2,300 hours.

Q. Harry Carswell (Carswell Engineering)
Are you using Australian or Canadian Coal?

A. Akihiko Tamura
At present coals from South Africa, U.S.A. and domestic coals are being tested. In the future we have many test programs including Canadian coal and also we are going to test the low volatile coals, which are abundant in Canada as well as South Africa, Australia and in Russia. We are interested in testing these types of low volatile coal.

Q. Ron Brown
Is there any possibility of using residual fuel oil in fluid bed combustion. I understand you used to use it directly in power generation.

A. Akihiko Tamura
We are not thinking of testing the heavy residual fuel oil at present. The purpose of immediate work is coal, maybe in the future we may test residual fuel oil for fluid bed combustion.

Sixth Speaker - Harry Yip (Pyropower)

Q. Roger Bailey (AOSTRA)
Could you tell us the estimate of the capital cost for the Gulf boiler in the States?

A. Harry Yip
I'm not a marketing man so I cannot tell you the exact number, but I can give you a range. For that unit, our scope of supply including the storage silo, all the way down to the stack - it's around 3 to 4 million dollar range and there is the coal yard and the preparation facility which in this case is not in our scope of supply for that particular site.

Q. Douglas Heaton
The largest capacity quoted was 400,000. Do you have any plans for going up to 1 million lbs/h, if so what sort of time frame are we looking at?

A. Harry Yip
By multiple boilers probably we can get up to 1 million lbs/h. At this time however, the largest one we offer is 400,000 lbs/h; in the conceptual design stage is a 800,000 lbs/h unit, due to a lot of interest in large size and from a utility point of view we are looking at that aspect.

There is some conceptual design effort in that stage. We believe in very orderly small scale-up steps. We go from pilot plant to 50,000 lbs/h, a ten fold scale up and then a 4 fold scale up to 200,000 lbs/h, a factor of 2 to 400,000 lbs. That much we have confidence in. A 800,000 lbs/h is certainly coming before Syncrude can make up their mind to move ahead or not.

Q. Ken Smith
You noted in one of your diagrams of the reactor, the combustor has a bottom ash discharge under the reactor zone itself. What is used to control that?

A. Harry Yip
That is the same type of control they use in Georgetown, Great Lakes and TVA. Basically you mean the withdrawal rate, the rate of withdrawing will be by bed Δ p, bed levels. We don't have a precise bed level so it is a matter of so much pressure drop and we know how much inventory we have in the combustion chamber.

Q. Frank Friedrich
With respect to the Kattua plant it showed a boiler efficiency of 86%. Is that based on higher or lower heating value?

A. Harry Yip
That was based on the design fuel, for peat lower heating value. Also, just to show the amount of work we will be doing, I want to mention the fact that by the summer we will have a pilot plant recirculating fluid bed in San Diego for further testing of any of these fuels, like petroleum coke or residual oil type tests.

Seventh Speaker - Bob Thompson (CANMET)

Comment by Mr. Duplessis (Alberta Research Council)

I would like to respond to Bob's request, that the Research Council shares the view that we would like to hear proposals from the private sector as to what their thoughts are on moving this technology ahead. We have got the opportunity here for government participation, both provincially and federally. I think we are probably taking the view here that we are looking for industry initiative to respond to. So you may be aware that there is the planning of the Devon Coal Research Centre. This is several years away, but still we are at an early enough stage to introduce certain aspects which need to be addressed. We are looking for industrial input to the planning of our coal program.